JOURNAL OF

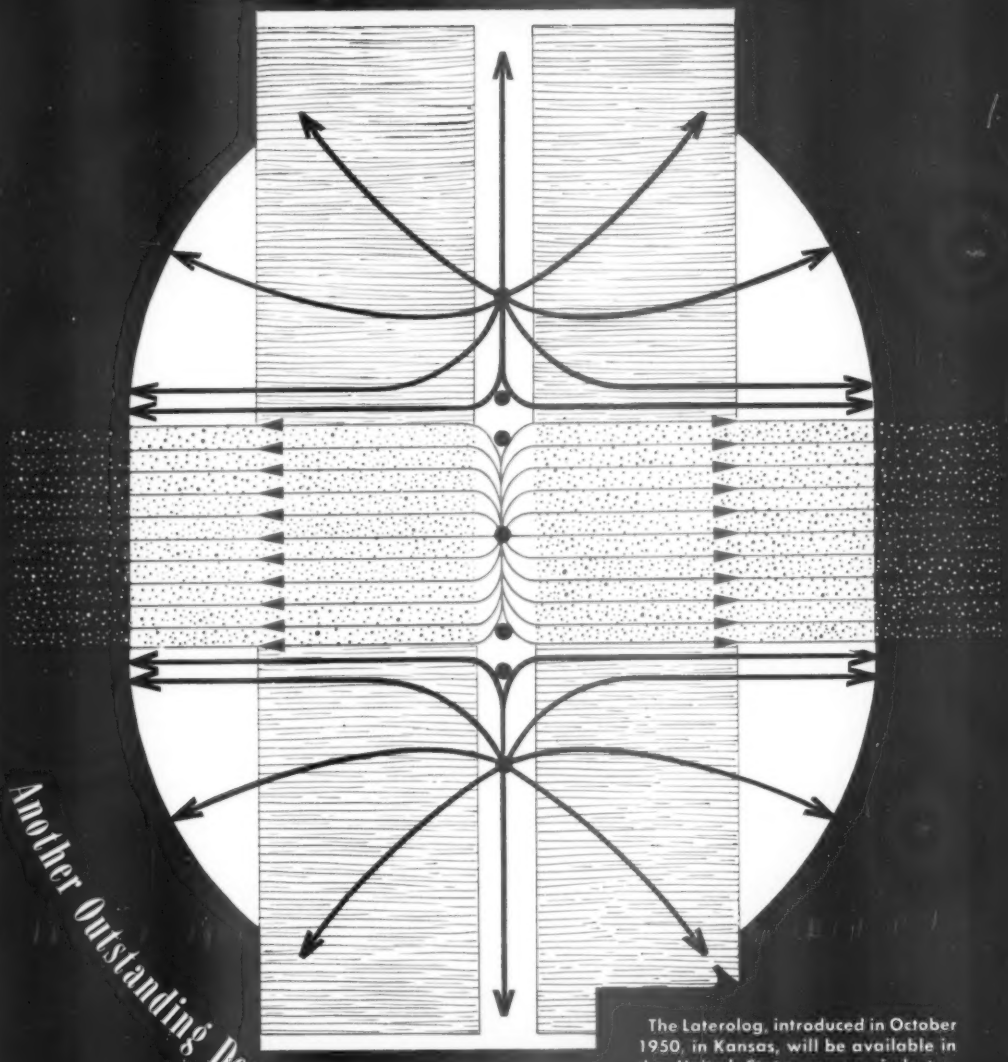
Petroleum Technology

OCTOBER, 1951

ANNOUNCING

The

LATEROLOG



Another Outstanding Development in Electrical Logging by SCHLUMBERGER

The Laterolog, introduced in October 1950, in Kansas, will be available in the United States on an industry-wide basis by January 1952. Write for further information.

SCHLUMBERGER

SCHLUMBERGER WELL SURVEYING CORP.

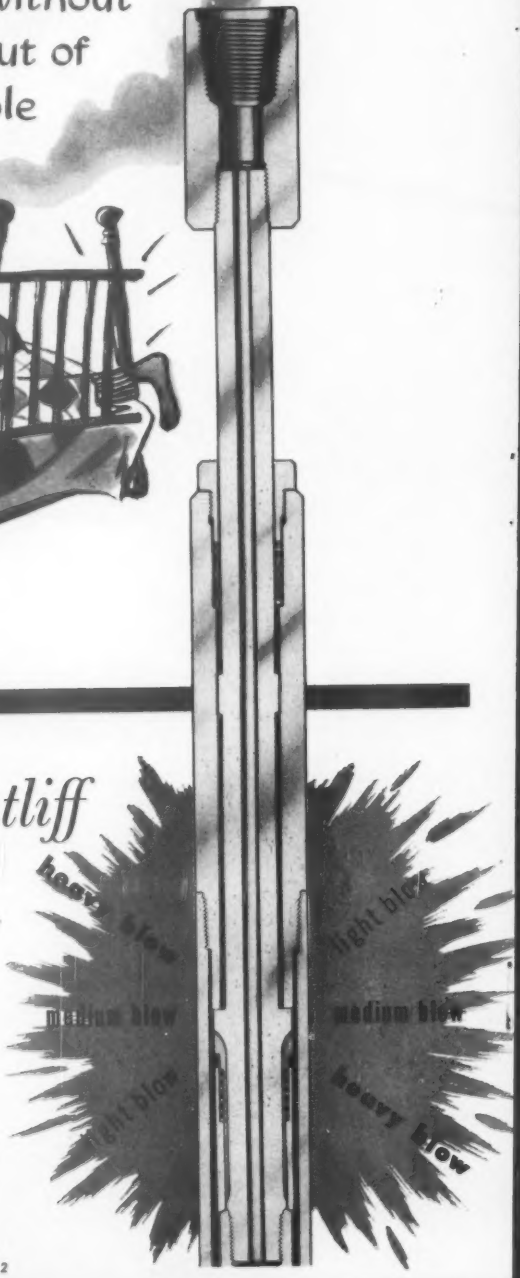
HOUSTON, TEXAS

FIELD TESTED
REMARKABLE RECORD FOR SAVING RIGTIME
A long list of triumphant field trials has earned top honors in the oil world for Halliburton's Retrievable Cementer.
It can be run in rapidly on tubing or drill pipe, set and used for a series of squeeze jobs, then immediately removed!
A remarkable saving in rigtime results, and wells are producing sooner by hours.
Your Halliburton representative will be happy to give you a detailed report.
"THERE'S NO SUBSTITUTE FOR EXPERIENCE IN OIL WELL CEMENTING"
NO METAL TO DRILL
LOCATE PERFORATIONS
PUMP CEMENT, ACID OR PLASTICS
PLACE CEMENT AROUND CASING SHOE
CEMENT IN OPEN HOLE
RUN MULTIPLE CEMENT JOBS
FIND AND REPAIR LEAKS
HALLIBURTON
RETRIEVABLE CEMENTER
HALLIBURTON OIL WELL CEMENTING CO.
DUNCAN, OKLAHOMA

The driller's dream come true...*

A jar that hits any desired blow, at any time, to meet any condition-without pulling out of the hole

*Jarring Jerry



The NEW *Johnston-Sutliff*

HYDRAULIC JAR

"The right jar for the job at hand"

Write For Descriptive Literature!

JOHNSTON

SHOOT TEST

M. O. JOHNSTON OIL FIELD SERVICE CORPORATION
3035 Andrita Street
Los Angeles 65, California
"Servicing California & Rocky Mountains"

M. O. JOHNSTON OIL FIELD EXPORT CORPORATION
3035 Andrita Street
Los Angeles 65, California
"Exclusive Export Sales"

SEE OUR EXHIBIT AT THE AIME SHOW IN BOOTH NO. 2

Journal of Petroleum Technology

Editorial Board

RICHARD W. FRENCH

JOHN E. SHERBORNE

THOMAS C. FRICK

*

Editorial and Business Staff

EDITORIAL DIRECTOR

JOE B. ALFORD

EDITOR

JESS E. ADKINS

ASSOCIATE EDITOR

VIRGINIA BEILHARZ

EDITORIAL ASSISTANTS

MARJORIE PARKS

BEKY YODER

Journal of Petroleum Technology is published monthly. Domestic Subscription: North, South and Central America, $8; foreign, $9; to AIME members, $6, or $4 if in combination with subscription to either Journal of Metals or Mining Engineering. Single copies 75 cents; special issues, $1.50. Registered cable address AIME. Printed in USA. Copyright 1951 by American Institute of Mining & Metallurgical Engineers.

Official Publication

Petroleum Branch

American Institute of Mining & Metallurgical Engineers

Statements and opinions contained in the JOURNAL are, unless otherwise indicated, attributable only to the author, and do not necessarily reflect the views of the AIME, its officers, committees, or other agencies.

Executive Secretary

JOE B. ALFORD

Editorial and Business Office

408 Trinity Universal Building

Ross at Harwood

Dallas, Tex.

STerling 4213 RIverside 9437

Officers of the Petroleum Branch

CHAIRMAN

Richard W. French
Sohio Petroleum Co.
Cleveland, Ohio

VICE-CHAIRMEN

Lincoln Elkins
Sohio Petroleum Co.
Oklahoma City, Okla.

Paul R. Turnbull
La Gloria Corp.
Corpus Christi, Tex.

EXECUTIVE COMMITTEE

John S. Bell
Humble Oil and Refining Co.
Los Angeles, Calif.

Harold Decker
Houston Oil Co. of Texas
Houston, Tex.

R. C. Earlougher
Earlougher Engineering
Tulsa, Okla.

Thomas C. Frick
Atlantic Refining Co.
Midland, Tex.

Richard J. Lund
Battelle Memorial Institute
Columbus, Ohio

John R. McMillan
Fullerton Oil Co.
Pasadena, Calif.

Harry H. Power
University of Texas
Austin, Tex.

Dean H. Sheldon
Consulting Engineer
South Pasadena, Calif.

John E. Sherborne
Union Oil Co. of Calif.
Whittier, Calif.

TREASURER

R. E. Heithecker
Seaboard Oil Co.
Dallas, Tex.

Branch Committee Chairmen and Vice-Chairmen

PUBLICATIONS COMMITTEE

J. M. Bugbee, Chairman
Shell Oil Co.
Houston, Tex.

John P. Hammond, Vice-Chairman
Amerada Petroleum Corp.
Tulsa, Okla.

MEMBERSHIP

Jack H. Beesley
Baroid Sales Division
Tulsa, Okla.

PRODUCTION REVIEW COMMITTEE

E. W. Berlin, Chairman
Standard-Vacuum Co.
New York, N. Y.

R. B. Gilmore, Domestic
DeGolyer and MacNaughton
Dallas, Tex.

A. H. Chapman, Foreign
Arabian American Oil Co.
New York, N. Y.

EDUCATION COMMITTEE

John C. Calhoun, Jr., Chairman
Pennsylvania State College
State College, Penn.

Harry H. Power, Vice-Chairman
University of Texas
Austin, Tex.

TECHNOLOGY COMMITTEE

Earl M. Kipp, Chairman
The California Co.
New Orleans, La.

Jack H. Abernathy, Drilling
Big Chief Drilling Co.
Oklahoma City, Okla.

Henry L. Waszkowski, Production
Magnolia Petroleum Co.
Oklahoma City, Okla.

E. G. Trostel, Natural Gas
DeGolyer & MacNaughton
Dallas, Tex.

Wayne E. Glenn, California
Continental Oil Co.
Los Angeles, Calif.

Officers of the AIME

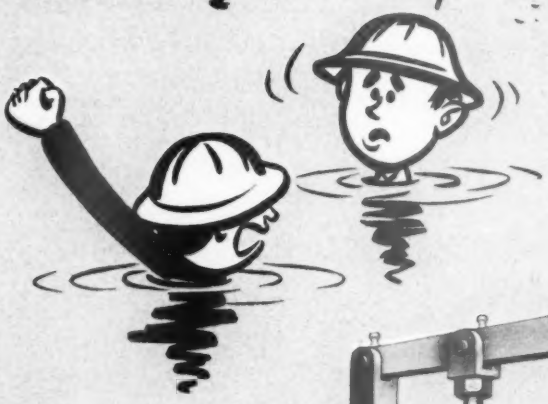
President, W. M. Peirce; Vice-Presidents, Joseph L. Gillson, Michael L. Haider, A. B. Kinzel, Philip Kraft, R. W. Thomas; Vice-President and Treasurer, Andrew Fletcher; Secretary, E. H. Roble.

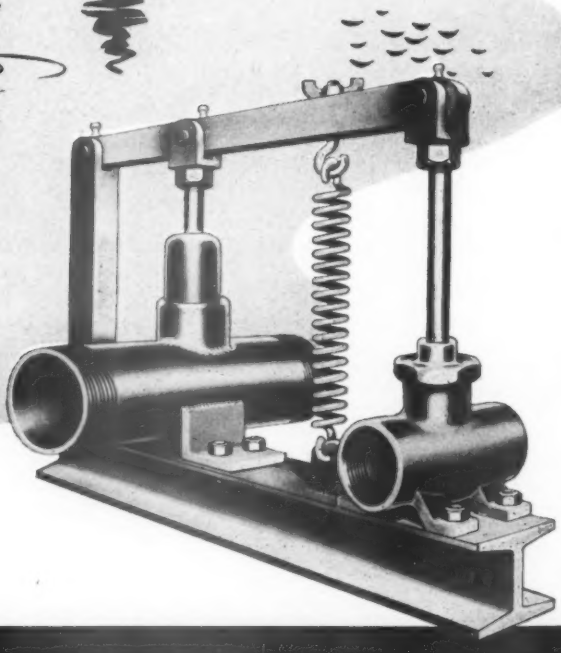
Journal of Petroleum Technology is published monthly by the American Institute of Mining and Metallurgical Engineers at 29 West 39th Street, New York 18, N. Y. Entered as second class matter January 31, 1949, at the post office at New York, N. Y., under the Act of March 3, 1879. Additional entry at Dallas, Texas.

Publisher's Representatives

Allen Associates	McDonald-Thompson		William R. Stewart
135 West 47th St.	3727 West Sixth St.	1118 Odeans Drive	Nine South Clinton St.
New York 19, N. Y.	Los Angeles 5, Calif.	Dallas, Texas	Chicago 6, Ill.

But Boss, I thought we had an A-1 Gardner Water Control Valve





Perfect mud control is automatic with the A-1 Gardner Water-Control Valve. The mud line from the pump and water line to the pit are connected parallel. When mud pressure drops, during shut-downs for coring or making connections, spring tension automatically closes the water valve. This saves your mud, water, and prevents water slugs forming. The tool is sold and shipped direct, domestic and foreign.

A-1 BIT & TOOL COMPANY

A-1

2000 HUSSION STREET • BOX 2133 • CHarter 7611 • HOUSTON

DISTRICT OFFICES AND SERVICE POINTS:

TEXAS
Corpus Christi
Victoria
Kilgore
Beaumont

CALIFORNIA
Los Angeles
Baash-Ross Tool Co.

LOUISIANA
Lafayette
Houma
New Orleans
Lake Charles

MISSISSIPPI
Brookhaven

OKLAHOMA
Oklahoma City

WYOMING
Casper
Baash-Ross Tool Co.
(Sidewall Coring, Casing Milling and Side Tracking Burris Key Seat Wipers)

ILLINOIS
Olney
Baash-Ross Tool Co.

CANADA
Import Tool Company, Ltd.
No. 10-620-8th Avenue West
Calgary, Alberta

EXPORT REPRESENTATIVES:

SOUTH AMERICA:
C. R. Summers,
Avila Hotel,
Caracas,
Venezuela

NEW YORK, N. Y.
Beckley, Haltom & Hickman
30 Rockefeller Plaza

ARGENTINA:
Langley y Cia.
Corrientes 1115
Buenos Aires

NEAR & FAR EAST
W. O. Calvert
20 Copthall Ave.
London E. C. 2
England

MEXICO
J. E. Douglas
2nd Natl. Bank Bldg.
Houston, Texas

THE PROFESSIONAL MAGAZINE FOR PETROLEUM ENGINEERS

Journal of Petroleum Technology

Vol. III | OCTOBER, 1951 | No. 10

TABLE OF CONTENTS

Editorial Features — Section 1

Editorial: "Made from Canadian Crude," by M. L. Haider 9
Iran and World Oil, by Charles J. Hedlund 10
Reefs in the Illinois Basin, Reported by R. G. Daley . . 13
Application of D.T.A. to Sub-Surface Correlations, Reported by D. B. O'Neill 14
Technical Note: The Interpretation of Chemical Water Analysis by Means of Patterns, by Henry A. Stiff . . 15
Technical Note: A Note on the Interrelationship Between Wetting and Non-Wetting Phase Relative Permeability, by M. R. J. Wyllie 17
Abstracts of Papers to be Presented at the Los Angeles Fall Meeting 18

Petroleum Transactions

Report on the Mamou Field Pressure Maintenance Project, by William O. Crego and James M. Henagan . . 263
Interstitial Water Determination by an Evaporation Method, by E. S. Messer 269
Fluid Saturation in Porous Media by X-Ray Technique, by A. D. K. Laird and John A. Putnam 275

Institute Affairs — Section 2

Drift of Things, by Edward H. Robie 2
Personals 4
Employment Notices 6
Petroleum Branch Membership 6
Advertisers' Index 8

On the Cover — Plant employees use the walkway running beneath brightly painted pipes at Humble Oil and Refining Co.'s gas plant at Opelousas, La. With the fractionator and absorber towers in the background, the plant takes the liquid products, natural gasoline, butanes and propane, from the gas before it goes to market to be burned as fuel.

B and W SCRATCHERS AND CENTRALIZERS FOR A GOOD CEMENT JOB

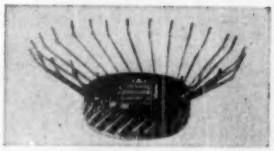
B and W LATCH-ON CENTRALIZERS

with the NEW KON-KAVE BOW

Strong[illegible] by test
Easier to Install

and

B and W Multi-Flex Scratchers



are a GOOD Combination for a GOOD CEMENT JOB!

B and W Incorporated

Well Completion Specialists

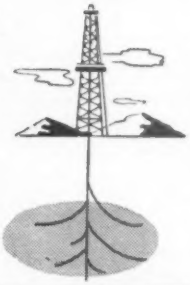
WEST COAST 3545 Cedar Avenue
Long Beach 7, California, Long Beach 4 8366
GULF COAST P. O. Box 5266
Houston 12 Texas. Phone WEntworth 6603

WHETHER IT IS PRIMARY OR SECONDARY RECOVERY

The BOTTLENECK IS AROUND The WELL BORE

Third of a Series

The greatest friction (Pressure Loss) occurs with greatest velocity of oil within the vicinity of the well. Large amounts of Reservoir Energy are required to force the oil from the formation to the well.



To *increase* Production means to relieve Friction and Pressure Loss. The drilling of a number of ZUBLIN DRAINHOLES into the surrounding oil sand *does the well the most good where it is most needed.*

ZUBLIN DRAINHOLES INCREASE PRODUCTION AND STOP WASTE OF RESERVOIR ENERGY AND WASTE OF WELL POTENTIAL

ZUBLIN DRAINHOLES GATHER THE OIL, FLOWING IT WITHOUT FRICTION TO THE WELL FOR BETTER

PRIMARY or SECONDARY } RECOVERY { IN NEW WELLS or IN OLD WELLS

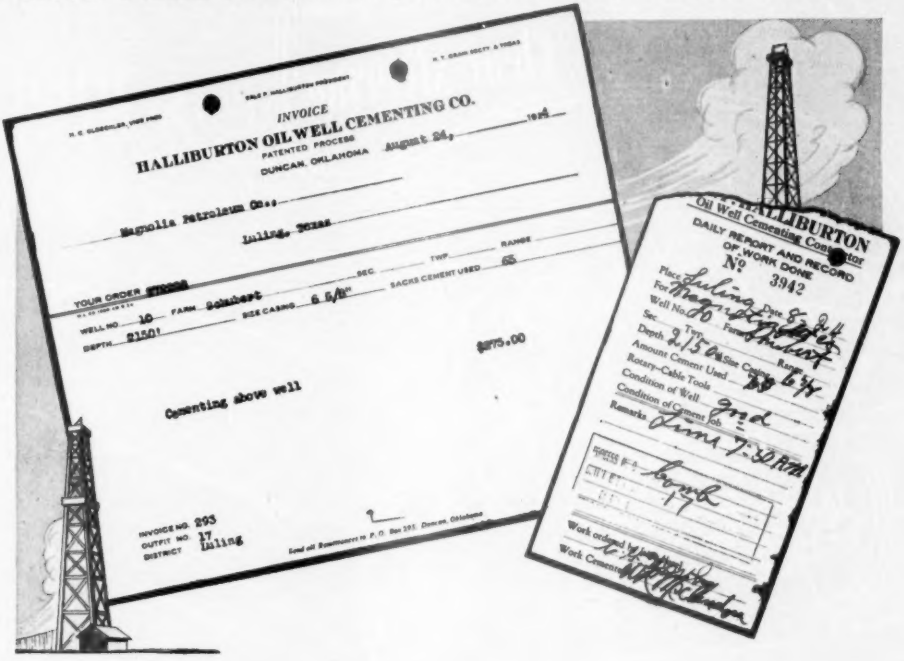
The first and second advertisements of this Series describe Zublin Drainholes and Flexible Drill Pipe. We shall be glad to send them to you.

ZUBLIN AND COMPANY

LICENSED MANUFACTURERS, OPERATORS AND DISTRIBUTORS OF ZUBLIN DRAINHOLE DRILLING EQUIPMENT

2369 EAST 51ST ST. TELEPHONES: JE 6151 JE 4433 LOS ANGELES 58, CALIFORNIA

BY ANY YARDSTICK... CEMENTING PRICES ARE LOW



Many things have happened since the invoice and job ticket reproduced above were written.

The man who signed the job ticket as cementer—W. R. McClendon—is now president of Halliburton Oil Well Cementing Company.

Wells have gone deeper and the price of everything we eat, wear or use has gone up according to the government's Consumers Price Index, which now stands at 185 plus.

But there is one item that is actually LESS today than the figure shown in this long-ago invoice of August 24, 1924—the cost of the average cementing job.

By any yardstick, Halliburton cementing prices are low.

Erle P. Halliburton

Chairman of the Company

HALLIBURTON OIL WELL CEMENTING CO.
Duncan, Oklahoma

33% MORE OIL after Dowell Selective Acidizing than after regular acidizing

Efficient acidizing is putting the acid in the zones that pay. That's the purpose of Dowell Selective Acidizing.

The Electric Pilot has been designed to enable Dowell engineers to steer the acid into the oil-bearing zones instead of letting the acid follow the path of least resistance. Dowell Selective Acidizing pays . . . as was proved in this case:

A new well was being treated for the first time. The microlog indicated two permeable zones in the well. After selective acidizing of these two pay zones with the accurate Dowell Electric Pilot, the completed well produced 33% more oil than nearby wells that were treated with the same amount of acid in the conventional manner.

Selective acidizing is useful in most old wells, particularly those with residual oil to be recovered from tight sections; those with high gas-oil ratios, or intermediate water zones; and those plugged back from bottom water or deepened to new pay zones. It is of value for new wells with saturated zones of varying permeability and those with a change of formation within the open hole.

Call the nearest Dowell office and ask for additional information about selective acidizing and the other Dowell Electric Pilot Services promptly available to you.

DOWELL INCORPORATED
TULSA 1, OKLAHOMA
Subsidiary of The Dow Chemical Company

DOWELL

SELECTIVE ACIDIZING

Ask your nearest Dowell station for complete information on these Dowell services and products: Acidizing Service, Electric Pilot Services, Plastic Service, Chemical Scale Removal for heat exchange equipment, Jelflake, Paraffin Solvents, Magnesium Anodes for Corrosion Control and Bulk Inhibited Hydrochloric Acid.

"First in Acidizing . . . since 1932"

Look to
DOWELL
FOR OIL INDUSTRY CHEMICAL SERVICE

Editorial Comment

"Now Made from Canadian Crude"

By M. L. Haider
Vice-President, Imperial Oil, Ltd.
Member AIME

LAST SPRING hundreds of service stations in Ontario blossomed out with brand-new banners. There is nothing very unusual in this because service stations bloom at all seasons of the year and it is quite common for motorists in Canada to be treated to as fine a crop of superlatives as anywhere on the continent.

The interesting thing about this display was that it didn't carry any superlatives but a simple request to switch to a certain brand of gasoline — "*Now Made from Canadian Crude*."

This statement must have struck visitors to eastern Canada as a new low in low-pressure advertising, but it's safe to assume that it did not have the same effect on Canadians. For Canada, the banners marked a very significant stage along the road to self-sufficiency in petroleum. Self-sufficiency is not a phobia with Canadians, but the advantages of domestic sources of energy are widely recognized, possibly as a result of Canada's aggressive development of its water-power resources for the production of electricity.

Since about 1900 consumers in Ontario had not used oil products containing any substantial proportion of Canadian crude oil. Yet Ontario has long been one of the major oil-consuming areas of Canada, and Canada has been, per capita, the second highest consumer of petroleum products in the world.

The "Canadian crude" referred to in the banners had come from oil fields 2,000 miles away in the province of Alberta. But the story behind the crude went back nearly half a century through a long and for the most part disappointing search for oil in many parts of Canada. Aside from two sizable fields and a handful of geological "teasers," no important discoveries were made until production was found at Leduc, near Edmonton, early in 1947.

From that time on, progress has been at record speed. The prairie provinces, formerly supplied in the main with imported products, have become self-sufficient both in crude and in refining capacity. Eleven hundred and twenty-six miles of pipe line was pushed across the prairies in 150 days during 1950. Together with two new lake tankers, the largest ever built, some additional vessels and extra storage capacity, a distribution system now exists that is daily handling about one-third of Canada's oil requirements. Potential production today could meet about half the nation's needs when additional transport facilities are available.

This rapid progress, achieved in a little more than four years, has turned Canada into an important oil-producing nation. Self-sufficiency in a vital form of energy has been brought in sight. A new stimulus and broader horizons have been opened up for a major area of North America. New economic and strategic strength have been contributed to this continent.

*

JOURNALISTIC friends tell me that an editorial should contain some information and should conclude with a moral.

On thinking it over, the interesting conclusion for me is that while this Canadian achievement would have been hailed with delight in any of those countries where four and five-year plans are touted, there was no "master" plan whatsoever. Instead, there were thousands of individual plans, ranging from those of individual consumers who required steadily increasing quantities of oil, to the plans of the many enterprises which undertook the work of producing oil and building facilities for its use and transportation. The only common threat in all these individual plans, and the only compulsion to which the individuals themselves were subjected, was the desire to better themselves.

That the individual plans and desires of consumers, investors and labor can spontaneously mould themselves into a vast project that is balanced, co-ordinated and swift of achievement would be regarded as impossible in some lands where planning is no longer a privilege of private citizens.

That such achievements do take place — in free countries — is something we should all remember. Still more important, we should remember *why* they take place.

★ ★ ★

An Industry Official Looks Backward a Few Years At Petroleum Production and Consumption and then Takes a Timely Look at

IRAN and WORLD OIL

By Charles J. Hedlund
Standard Oil Co. of N. J.

OIL is an international business. During recent months, the dispute in Iran has driven home this fact to millions of citizens of the western world. The man on the street is increasingly aware that the various functions and areas of the world oil industry are so closely connected that a major change in any one branch or any one region may have repercussions throughout the world. At the same time, there has been much misunderstanding about the part played in the world oil scene by foreign oil in general, and Iranian oil in particular. A brief review of the world demand and supply trends may be of aid to all of us in understanding some of the important foreign oil problems facing the industry.

The Growth of Petroleum Consumption

The world's use of oil has grown so steadily and rapidly as to exceed consistently the expectations of the most optimistic prophets. World consumption of petroleum in 1950 (excluding Russia) totalled somewhat over 10,000,000 B/D, about double the 5,000,000 B/D level of consumption just prior to World War II. In the last four years (1946-1950), world demand has jumped upward by 3,000,000 B/D. This compares to a growth of only about 2,000,000 B/D in the preceding *eight* years, when foreign demand was depressed by the unsettled conditions of World War II.

It is interesting to observe the geographical distribution of the world's oil consumption. As shown in Fig. 1, almost two-thirds of the world's petroleum was consumed by the United States in 1950. Foreign requirements may be visualized as being split into three roughly equal segments. Canada and the Latin American nations in the Western Hemisphere consumed about 1,200,000 B/D in 1950. The ECA countries used nearly 1,200,000 B/D, while an additional volume of approximately 1,300,000 B/D was spread out over the vast areas and vast population throughout the balance of the Eastern Hemisphere.

Russian consumption is believed to be in the neighborhood of 800,000 B/D.

Although foreign oil requirements are still much less than those of the United States, a more rapid rate of growth is being registered in the foreign markets. From 1946 to 1950, United States consumption of petroleum increased about 7.3 per cent per year on the average. Foreign demand, on the other hand, grew 13.2 per cent per year during this period.

There is a tremendous potential market for petroleum products in foreign countries. The transportation facilities of most foreign countries are woefully inadequate by United States standards. The home heating market, which has been developed so extensively in this country, has hardly been touched abroad. The vast difference in level of consumption in the United States, as compared to foreign countries, is brought out in Fig. 2, which shows the petroleum demand per capita in the United States as compared to all foreign areas, excluding Russia. Notice that the scale of the lower chart has been enlarged about 20 times, as compared to the upper chart. In 1950, the United States used more than 15 bbl per person, more than 20 times as much as the approximately seven-tenths of a bbl per person used abroad. Some of the more highly industrialized foreign nations, of course, approach the United States more closely than would be indicated by this average figure. Canada's consumption per capita in 1950 was about nine bbl. On the other hand, in a highly industrialized country like the United Kingdom, consumption per capita is only about one-sixth that of the United States.

In the United States, consumption per capita seems to be developing more nearly in accordance with long-term trends. Most people who have studied the trends in requirements expect some falling off in the rate of growth here in the United States. But there has been no evidence of serious weakening in the last two years. In 1950 United States consumption grew 12 per cent, or about 700,000 B/D. A further gain of 10 per cent or more than 600,000 B/D seems likely in the present year 1951.

It is easy enough for us to speak of an increase of 600,000 to 700,000 B/D consumption per year. But we may comprehend the magnitude of such a growth by recalling that it requires development of additional supplies each year equivalent to more than the entire crude oil output of Oklahoma.

World Crude Production

In turning to the supply side of the world oil business, as shown in Fig. 3, one is immediately reminded that crude production is distributed quite differently from demand. The United States is nearly self-sufficient, producing somewhat over half the world's crude oil. On the other hand, the European countries, the area of most concentrated foreign demand, have almost no crude production. The two major foreign producing areas of the Caribbean and Middle East each con-

	THOUSANDS OF BARRELS PER DAY	PERCENT OF WORLD
UNITED STATES	6,500	64
OTHER WESTERN HEMISPHERE (CANADA & LATIN AMERICA)	1,220	12
ECA COUNTRIES	1,160	11
OTHER EASTERN HEMISPHERE	1,330	13
TOTAL FOREIGN	3,710	36
WORLD (EX. RUSSIA)	10,210	100

FIG. 1 — WORLD PETROLEUM CONSUMPTION IN 1950 (EXCLUDING RUSSIA).

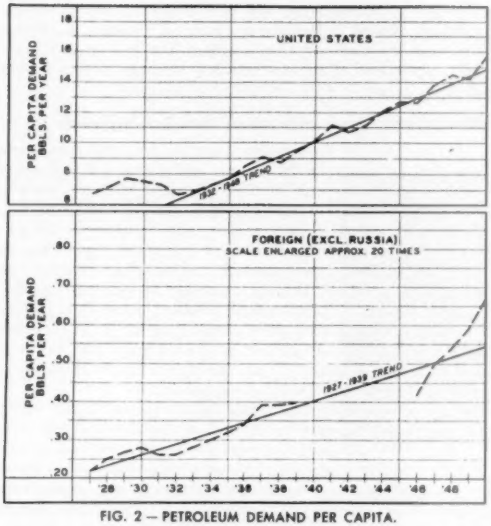

UNITED STATES
PER CAPITA DEMAND BBLS. PER YEAR
1932 - 1949 TREND
FOREIGN (EXCL. RUSSIA)
SCALE ENLARGED APPROX. 20 TIMES
PER CAPITA DEMAND BBLS. PER YEAR
1927 - 1939 TREND
'28 '30 '32 '34 '36 '38 '40 '42 '44 '46 '48

FIG. 2 — PETROLEUM DEMAND PER CAPITA.

tributed in the neighborhood of 1,700,000 B/D of crude oil supplies during 1950. Surpluses from these major producing regions covered the needs of Europe and the rest of the widely dispersed foreign demand and, in addition, augmented supplies in the United States.

The long-term trend of world crude oil production, as illustrated in Fig. 4, is a picture of generally increasing production. It may be observed that 1950 production is just about double the immediate prewar figure. With the exception of the war-rationing year of 1942, the only declines in world crude oil production have occurred during periods of depressed economic activity. A major depression such as that of the '30's seems to set back the growth curve by about five years, whereas minor recessions such as those of 1938 and 1949 seem only to delay the growth of the industry for about one year.

Perhaps the outstanding postwar development in foreign crude oil production has been the rapid rise of the Middle East as a supply source. At the close of World War II, the six Middle East oil producing countries had a total output of around 500,000 B/D, only about two-thirds as much as the production in Venezuela. The postwar years have seen a rapid development of Middle East crude oil supplies, designed primarily to supply Eastern Hemisphere markets. The result has been that in 1950, Middle East crude production reached nearly 1,800,000 B/D. While Venezuela has shown a steady growth in production, the total production of the Middle East countries now exceeds that of Venezeula. Later, some of the more recent developments in the Middle East which have taken place since the Iranian dispute broke out in March will be outlined.

Crude Oil Reserves

The distribution of crude reserves between the United States and foreign areas is almost the reverse of the distribution of production. According to the best data I am able to assemble, the world proved reserves of crude and light hydrocarbons, excluding Russia, are about 100 to 115 billion bbl, of which only 30 billion bbl are located in the United States and 70 to 85 billion bbl abroad. Thus, the United States is producing more than 50 per cent of the world's oil from only 25 to 30 per cent of the world's proved crude oil reserves.

Proved reserves represent only those deposits whose presence has actually been proved with the drill. I like to think of proved reserves as being only the underground working inventories of the petroleum industry, similar to the above-ground storage in tanks. The error is often made that proved reserves are indicative of the ultimate supplies of oil. This, of course, is not true. There is a lot of oil yet to be found in the United States, as witnessed by the fact that we are finding more oil than we produce each year, and yet one cannot help but be impressed by the magnitude of foreign crude oil reserves.

The geographical distribution of crude reserves suggests that we cannot overlook the importance of the foreign oil resources to the domestic oil picture. Over the long pull, the United States may require increasing amounts of imported oil as well as increased domestic production in order to cover its requirements.

World Refining

Increases in crude production alone do not suffice to take care of expanding requirements. Additional refining capacity is also needed. Here in the United States, refining capacity is being expanded to meet our needs. A recent report of the "Million Barrel" Committee of the National Petroleum Council indicated that U. S. refiners plan to construct approximately 1,000,000 B/D of additional refining capacity by the middle of 1953.

Most of the foreign refining capacity now being installed is being located in the consuming countries. This reflects the desire on the part of many nations to conserve foreign exchange by purchasing from outside the cheaper raw crude oil and refining it at home for local currencies. In Europe, particularly, there has been a rapid expansion of refining capacity since the war. With the help of ECA financing in some cases, over 700,000 B/D of new refining capacity has been installed in Europe since the war. This has had the result of essentially tripling the European capacity.

The gain in European refining capacity and rising Middle East crude production has tended to make the Eastern Hemisphere more and more independent of Western Hemisphere supplies. Since 1949, the Eastern Hemisphere has no longer been a net importer of crude oil from the Western Hemisphere. Substantial quantities of products are still exported to Eastern Hemisphere markets from Caribbean and U. S. Gulf refineries, but this movement was on the decline until temporarily reversed by the shutdown of the great Abadan refinery. It is reasonable to expect that, regardless of the course of events in Iran, the Eastern and Western Hemispheres will eventually emerge as two more or less independent oil producing and consuming areas, with some continuing flow of marginal volumes between the hemispheres.

	CRUDE AND LIGHT HYDROCARBON PRODUCTION		DEMAND	
	THOUS. B/D	% OF WORLD	THOUS. B/D	% OF WORLD
UNITED STATES	5,900	58	6,500	64
CARIBBEAN	1,650	16		
OTHER WESTERN HEMISPHERE	410	4	1,220	12
E.C.A. COUNTRIES	80	1	1,160	11
MIDDLE EAST	1,760	17		
OTHER EASTERN HEMISPHERE	430	4	1,330	13
WORLD (EX. RUSSIA)	10,230	100	10,210	100

FIG. 3 — GEOGRAPHICAL DISTRIBUTION OF WORLD PETROLEUM DEMAND AND PRODUCTION IN 1950 (EXCLUDING RUSSIA).

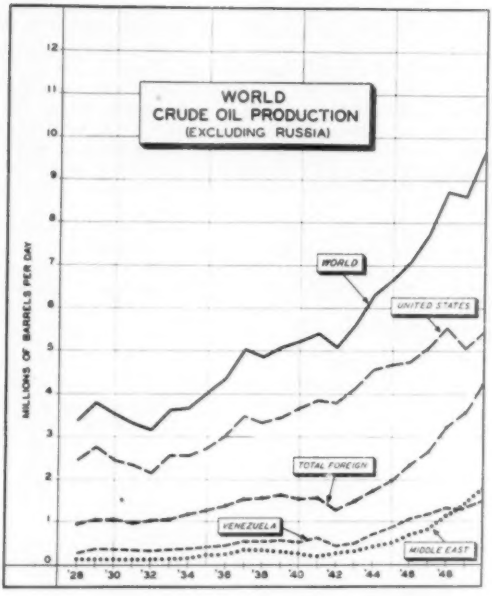


FIG. 4 — WORLD CRUDE OIL PRODUCTION (EXCLUDING RUSSIA).

The Iranian Crisis

Most of my points so far have been based upon the conditions in the world oil business in 1950 while the Iranian supplies were still available to the world market. Most readers are familiar with the nationalization of the Iranian oil industry decreed by the Iranian government and the long negotiations which have ensued with the British owners of the Iranian oil properties. The issues are many and complex, and the principles involved are more important from a long range standpoint to the free world than the physical volume of oil in jeopardy. This paper, however, will limit itself to the physical aspects of the picture and leave for discussion elsewhere such important principles as the necessity of mutual confidence and respect for property rights without which international flow of capital and trade so essential to the economic development of the world would be stagnated.

Long-Term Replacement of Iranian Supplies

While the Iranian oil supplies are important to the petroleum industry and to the western democracies, they are by no means irreplacable. From the long-term standpoint, other petroleum supply sources are capable of taking on the requirement.

Iran's crude production recently averaged about 650,000 B/D. This is a large volume of oil, but it is equivalent to only a little more than one-tenth of the current crude oil production in the United States and only about one-fifteenth of world production. The huge refinery at Abadan averaged about 500,000 B/D thruput, but this is only 5 per cent of world refinery operations.

The world oil industry is fully capable of replacing the Iranian production from other sources In a relatively short period of time. In 1950 world demand rose by 1,140,000 B/D over the previous year. A further growth of over 1,000,000 B/D is expected this year. In order to meet these sharp increases in consumption, the oil industry all over the world has been rapidly expanding its crude oil production, refining capacity, and transportation facilities. The loss of all Iranian oil is equivalent to substantially less than the annual growth of the industry in either of the past two years.

Short-Term Replacement of Iranian Supplies

Let us look at the Iranian problem from the immediate practical viewpoint. In the event no settlement can be reached in Iran, the short-term problem over the next few months appears to be one of rearranging world crude and product supplies on an emergency basis in order to meet the requirements of the petroleum markets all over the world. Specifically, the problem involves replacement of about 150,000 B/D of crude oil normally shipped from Iran as such and approximately 450,000 B/D of refined products normally exported from Abadan (equivalent to about 500,000 B/D of crude charging capacity). Expressed in another way, there has been lost from the industry picture about 650,000 B/D of crude and 500,000 B/D of refining capacity.

Let us first examine the crude supply picture. Fig. 5 shows the increases in crude production of various countries since March, when the Iranian trouble began. You will notice that the bulk of the crude shortage has already been made up by the higher levels of crude production in the neighboring Middle East countries of Arabia and Kuwait. Since March, 1951, the total increase in world crude production, excluding Iran, has been over 800,000 B/D, or *more* than the total production lost in Iran. Thus, in this sense, the Persian crude has already been replaced. In addition, there has been sufficient increase to allow some further growth in world requirements.

Refining capacity is a bit more of a problem. The world crude refining industry was already operating at high levels before the Iranian trouble arose. However, considerable added foreign refining capacity is being put into operation on an emergency basis. New plants constructed in Europe, such as the 125,000 B/D plant recently opened at Fawley, England, will help to fill the gap. In addition, strenuous efforts are being made to increase the thruput at existing plants. The product shortage is pretty well covered through the balance of the year by increases in output of foreign refineries, plus product purchases in the United States.

The British companies have an extensive program of purchasing refined products in the United States. More than 25,000,000 bbl of products of all kinds have been purchased for lifting during the last half of this year. The peak rate of purchase thus far was scheduled for September, and amounted to over 250,000 B/D of products. United States crude and products stocks are high and the present level of operations is more than adequate to support consumption.

Continued on Page 8, Section 2

	MARCH 1951	AUGUST 1951	INCREASE SINCE MARCH
UNITED STATES	6,052	6,227	+ 175
VENEZUELA	1,678	1,707	+ 29
CANADA	80	168	+ 88
ARABIA	639	838	+ 199
KUWAIT	375	700	+ 325
OTHER, EX. IRAN AND RUSSIA	1,244	1,265	+ 21
TOTAL WORLD, EX. IRAN & RUSSIA	10,068	10,905	+ 837
IRAN	698	——	— 698
TOTAL WORLD, EX. RUSSIA	10,766	10,905	+ 139

FIG. 5 — INCREASE IN WORLD CRUDE OIL PRODUCTION SINCE MARCH, 1951 (THOUSANDS OF BBL DAILY).

Reefs in the Illinois Basin

Reported by R. G. Daley
Illinois Basin Chapter

David H. Swann, geologist with the Oil and Gas Division of the Illinois State Geological Survey, was speaker for a recent meeting of the Illinois Basin Chapter. A summary of his paper on "Reefs in the Illinois Basin" is given below.

At the present time any lenticular body of massive carbonate rock clearly distinguishable from the surrounding strata is called a reef or bioherm, particularly if the rock is at all fossiliferous. A true reef also stood well above the sea floor during its deposition and was wave-resistant because it was partly constructed by organisms which would act as binders. This distinction between true reefs and other reef-like bodies is important in guiding exploration because true reefs were able to contribute much more debris to the enclosing sediments than were other types of reef-like bodies which never stood far above the sea floor. In the Illinois Basin true reefs are apparently confined to the middle Silurian strata. The Silurian seas were too deep in the central part of the basin to allow the growth of reefs, and therefore the reefs are confined to the margins of the basin, particularly on the northeastern and northwestern flanks.

ILLINOIS BASIN CHAPTER OFFICERS — New officers of the Illinois Basin Chapter are, L. to R., R. G. Daley, Journal secretary; D. M. Moon, secretary-treasurer; J. R. Vaughan, Jr., second vice-chairman; Bob Diggs Brown, chairman; L. W. Swanbeck, first vice-chairman; and J. A. McCarty, director.

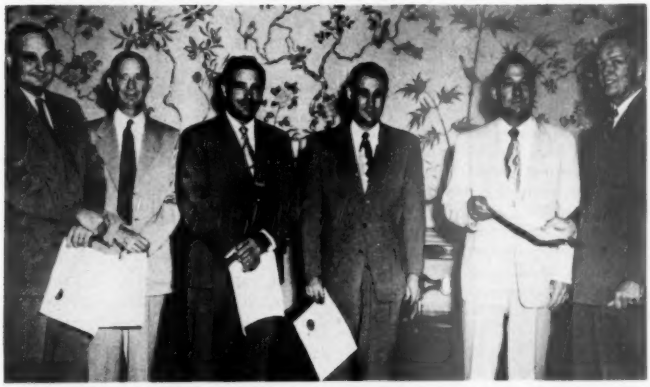
At the present time there are between 25 and 30 oil fields in Illinois and Indiana formed by Silurian coral reefs. Oil is produced in most of these fields only from younger strata draped over the reef, due to greater compaction of the non-reef Silurian strata than of the reef. In only five or six fields does the reef core itself actually produce commercial amounts of oil.

There are no examples of barrier reefs known in this area. The reefs occur in clusters. Single reefs vary in extent from a few acres to perhaps six or eight square miles and are usually oval in outline. The larger ones may approach horse-hoof or horse-shoe shapes, as does Marine Field Reef, the largest producing one yet found. The reef cores are exceptionally pure limestone or dolomite over 98 per cent soluble in acid, while the surrounding non-reef strata are silty and shaly limestones and dolomites containing 20 to 40 per cent insoluble material. Exploration methods depend either on physical differences between reef and non-reef Silurian strata, recognition of nearness to a reef by increasing purity of the Silurian sediments, the structure of the reef top itself or of the overlying beds draped over it, or variations in thickness of these overlying beds.

Reef pools were found as early as 30 years ago by random drilling and by the structure of coal beds draped over the reef cores, though recognition that the structures were caused by reefs has only come very recently. Currently the seismograph is the most successful tool, though one reef has recently been discovered by subsurface structure and another by strictly surface geology.

The reservoir engineering aspects of younger producing zones draped over Silurian reefs appear identical to those of the same beds in nearby deforma-

Continued on Page 5, Section 2



HONORED BY SOUTHWEST TEXAS SECTION — The Board of Directors of the Southwest Texas Section last month awarded certificates of merit to five of its members "in grateful appreciation of meritorious services rendered the petroleum industry in promotion of Petroleum Branch, AIME, work." Recipients of the award are, L. to R., H. N. Lyle, Charles S. Snelson, Raoul J. Bethancourt, R. C. Granberry, Jr., and Paul R. Turnbull. Lee J. Thronson, right, chairman of the Section, makes the presentations.

Application of D. T. A. to Sub-Surface Correlations

Reported by D. B. O'Neill
Pacific Junior Group

At a recent meeting of the Junior Group of the Pacific Petroleum Chapter, Henry M. Kilian, head geologist for Oil Properties Consultants, explained the potential application of Differential Thermal Analysis to the problem of subsurface correlation and how it may be used to advantage in the absence of data from known techniques. D.T.A. employs a method of analysis of clay as devised by Le Chatelier in some early studies.* The process utilizes the principle of quantitative proportionality of a qualitative mineral constituent found to come from the same parent source, this constituent, in the case of D.T.A., being clay. Kilian briefly mentioned the part clay analysis plays in the ceramics industry and discussed early experiments performed by people in that work which resulted in better, more consistently satisfactory products.

Kilian pointed out that field development engineers at present have to rely on data from core analyses, paleontology and various logging techniques for aid in subsurface correlation. In general, these means are satisfactory, but there are instances (for example in a long, monotonous shale section which is barren of microfaunal information) in which additional correlative tools are required. By utilizing to advantage the part that clays may play in the origin and accumulation of petroleum and in development practices, the speaker feels that differential thermal analysis as an analytical tool can and probably will play an important part in subsurface petroleum engineering and geological work in the future. In addition, since clays may also play a significant part in water flooding operations and other secondary recovery programs, the speaker feels that D.T.A. will also have applications in this field. D.T.A. is also able to isolate the presence of a fault in a long shale section which is void of microfaunal evidence and has been used to pick up unconformities.

Kilian then discussed the principles of operation of D.T.A. He stated that when heat is applied to hydrous mineral substances, loss of water, oxidation, decomposition and structural changes are known to occur. These reactions are accompanied by exothermic and endothermic effects. When the thermal effects of a sample are compared to a material that undergoes no thermal change (*i.e.*, a "standard"), a temperature difference results, which may be recorded in a differential thermal curve. The materials are both heated to 1,000° C within a time period of one hour and a half, this particular period having been settled on as producing the most significant results without obtaining the unnecessary detail and possible anomalies that might result from a longer heating period. No especially significant results are obtained until the temperature rises above 573°C. This is the temperature at which Alpha quartz changes to Beta quartz and the more important breakdowns in the latticework of crystal structures occur, which apparently have an important bearing on the use of D.T.A. for correlation. In summary, Kilian stated that through D.T.A., a qualitative analysis of a mineral sample is achieved through the application of heat.

The equipment employed for these operations consists of four main items; namely, an electric furnace, a control which assures a constant temperature rise, a sample holder and the various recording instruments. At present, Kilian stated, it is possible to run 12 samples per day, but that they hope soon to have in use a multiple recording device which could handle 100 samples a day.

The D.T.A. process is primarily concerned with the clay mineral groups, consisting of kaolinite, montmorillionite, illite, the miscellaneous crystal group, and the amorphous group, each one of which, said Kilian, possesses a rigid crystal form and is fairly regular. Kilian stressed that the engineer must be aware of the genesis of a certain rock or rock series involved; that he must realize that clay can be the end product of a certain geologic process only so long as no environmental change takes place. Quick changes in environment can cause abrupt alterations in the condition of possible reservoir rocks. Diagenetic changes are also important and, he feels, may take place rapidly, in general. Moreover, the character of the source material is important also in defining which of the five above clay mineral groups a certain sample may be derived from. For example, Kilian mentioned that montmorillionite clays

Continued on Page 5, Section 2

HENRY M. KILIAN, head geologist for Oil Properties Consultants explains a view of a recording chart and oven during his talk on D.T.A. before the Pacific Junior Group.

*"The Action of Heat on Clays," Bull. Soc. Franc. Min. 10, pp. 204-211, 1887.

Technical Note 84——

THE INTERPRETATION OF CHEMICAL WATER ANALYSIS BY MEANS OF PATTERNS

HENRY A. STIFF, JR., MEMBER AIME, ATLANTIC REFINING CO., DALLAS, TEX.

ABSTRACT

The classification and correlation of water analysis data presents many problems which can be solved by graphic methods. The pattern system, a new type of graphic procedure described in this communication, is believed to have several advantages over older methods. Examples of the application of the pattern system to the solution of problems encountered in petroleum production are given.

INTRODUCTION

Several graphic methods for presenting analytical water data have been developed and are now in use.[1,2,3,4] It is believed, however, that a recently developed type of graph called the "pattern" offers several advantages over other methods. This system presents a better picture of the total salt concentration than is usual in such graphs. The effect of dilution or concentration has been reduced to a minimum, and at the same time distinction between various types of water has been improved. The system is extremely versatile, yet so simple it can be plotted on ordinary graph paper and adapted to almost any type of filing system.

DISCUSSION

The essential feature of the pattern system is the graph shown in Fig. 1. Horizontal lines extending right and left from a vertical line at zero form the graph. Positive ions are plotted to the left while negative ions are plotted to the right. The figure immediately beneath each ion gives the scale. Most oil field waters can be plotted on a scale where 100 milliequivalents of sodium and chloride and 10 milliequivalents of each of the other ions are represented by one scale unit. For highly concentrated brines, 1,000 milliequivalents of sodium and chloride and 100 milliequivalents of each of the other ions are represented by one unit. For convenience sodium, potassium, lithium, etc., ordinarily determined as the difference between the positive and negative ions, are referred to as sodium.

It will be noted that the chemical unit of "milliequivalents per liter" is employed. If the results of the analysis are in parts per million, they can be readily converted by dividing by the equivalent weight in milligrams or multiplying by its reciprocal. Appropriate conversion factors can be found in standard chemical handbooks.[5]

When the points have been properly placed on the graph, they are connected by lines as shown in Fig. 2, thus forming a closed "pattern." These patterns present a variety of shapes and sizes, each easily recognized and remembered and each characteristic of a certain water.

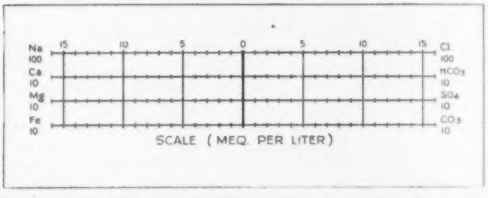


FIG. 1 — ESSENTIAL FEATURE OF THE PATTERN ANALYSIS SYSTEM.

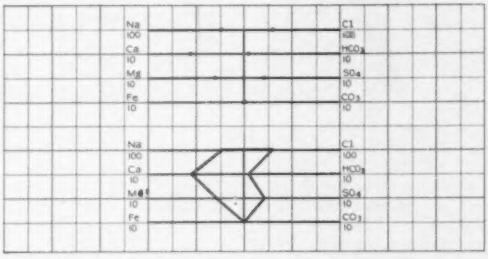


FIG. 2 — METHOD OF CONSTRUCTING A PATTERN.

Fig. 3 shows some common water patterns, including those of fresh water, sea water, chemical solutions and oil field brines. The straight line pattern of fresh water shown in the first diagram results from the use of a scale ordinarily employed for oil field brines. Any system of scales thought suitable to a particular operation may be used. Single scales, in which all ions are represented by an equal number of units, are used in plotting fresh waters, while multiple scales, in which all ions are not represented by the same number of units, find application in work with oil field waters. Various types of multiple scales can be used to advantage in water treatment work, corrosion control, and injection water studies.

One of the distinctive features of the system is the tendency of the pattern to maintain its characteristic shape as the sample becomes dilute. In this way the total salt concentration as well as the chemical composition of the water is shown by the pattern.

The availability of various scales makes it possible to select one which emphasizes the differences and similarities of the waters being studied, thereby making direct comparison and correlation between these waters possible.

Another very valuable feature of this system is its extreme simplicity. The pattern can be constructed by anyone on

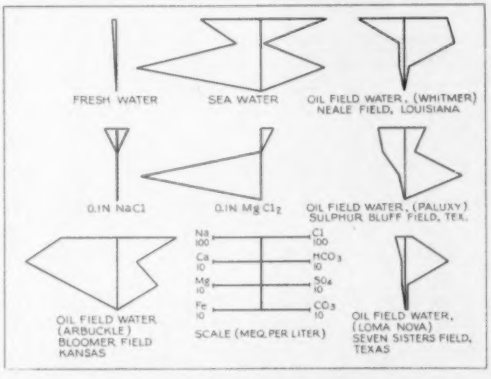

FRESH WATER
SEA WATER
OIL FIELD WATER, (WHITMER) NEALE FIELD, LOUISIANA
0.1N NaCl
0.1N MgCl2
OIL FIELD WATER, (PALUXY) SULPHUR BLUFF FIELD, TEX.
OIL FIELD WATER (ARBUCKLE) BLOOMER FIELD KANSAS
SCALE (MEQ.PER LITER)
OIL FIELD WATER, (LOMA NOVA) SEVEN SISTERS FIELD, TEXAS

FIG. 3 — COMMON WATER PATTERNS.

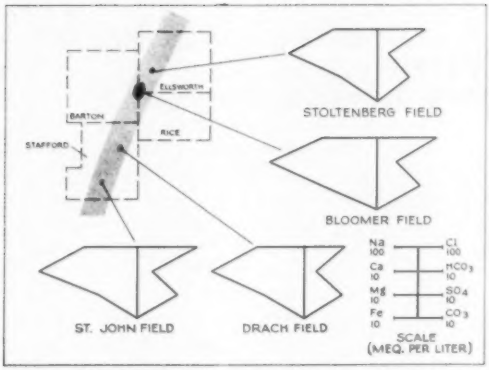


FIG. 4 — COURSE OF ARBUCKLE FORMATION THROUGH KANSAS SHOWN BY WATER PATTERNS.

ordinary graph paper. The use of a printed card containing a graph similar to that shown in Fig. 1, and in addition blank spaces for pertinent well data, is very convenient for this work. By this means a large and very useful library of patterns can be built up in a small space.

APPLICATION

The applications of the pattern system are many and varied. It is believed that this system will facilitate the solution of almost any problem in which water analysis is a factor. The following examples illustrate its application to various problems encountered in petroleum production.

Correlation of Producing Formations

Since the pattern tends to maintain its shape upon concentration or dilution, a formation may be expected to yield water of a characteristic pattern. A study of the water patterns can, in many cases, be utilized to identify different producing strata and correlate them in a given locality. In Kansas, for example, the Arbuckle group of the Ordovician period can be traced from Ellsworth County down through Barton County and into Stafford County by means of water patterns. Fig. 4 shows patterns from Stoltenberg Field (Ellsworth County), Bloomer Field (Barton County), and Drach and St. John's Fields (Stafford County). The characteristic pattern of the Arbuckle formation can be easily followed.

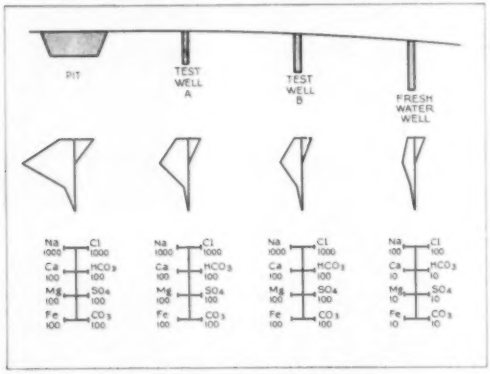


FIG. 5 — PATTERN ANALYSIS USED AS A TRACER.

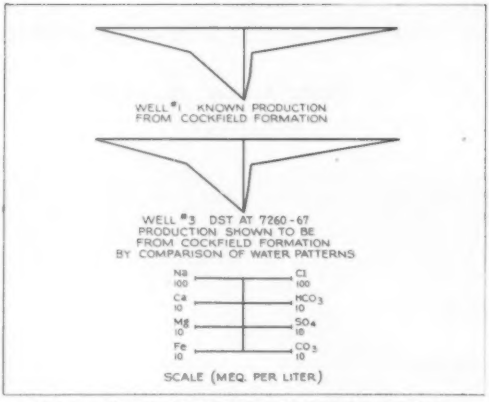

WELL #1 KNOWN PRODUCTION FROM COCKFIELD FORMATION
WELL #3 DST AT 7260-67 PRODUCTION SHOWN TO BE FROM COCKFIELD FORMATION BY COMPARISON OF WATER PATTERNS
Na 100
Ca 10
Mg 10
Fe 10
Cl 100
HCO3 10
SO4 10
CO3 10
SCALE (MEQ. PER LITER)

FIG. 6 — PATTERN ANALYSIS USED IN DRILL STEM TESTING.

Tracer Problems

It is often possible to trace the passage of water through a sand by a study of the patterns obtained from properly spaced test holes along its path. In the case presented in Fig. 5, seepage of salt water from a disposal pit into a fresh water well was suspected. Shallow test holes were drilled at *A* and *B* and allowed to fill by seepage. Samples were taken, the water analyzed, and the patterns plotted. The appearance of the disposal pit pattern, somewhat reduced in size, definitely established seepage in the direction of the well. When a sample from the fresh water well plotted on a magnified scale gave the same pattern as the pit, contamination became evident.

Drill Stem Testing

Because of the uncertainty regarding contamination of water samples by drilling mud encountered in drill stem testing, attempts to establish the formation from which such samples originate are often unsuccessful. In some cases, however, this information is extremely helpful. Because of the ease with which one pattern can be compared with another, the pattern system is especially useful for this purpose. Fig. 6 shows the

Continued on Page 3, Section 2

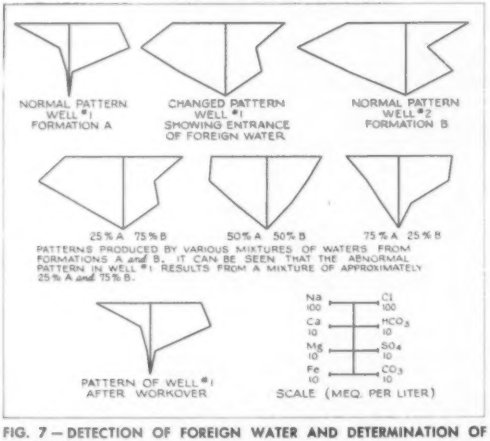

NORMAL PATTERN WELL #1 FORMATION A
CHANGED PATTERN WELL #1 SHOWING ENTRANCE OF FOREIGN WATER
NORMAL PATTERN WELL #2 FORMATION B
25% A 75% B
50% A 50% B
75% A 25% B
PATTERNS PRODUCED BY VARIOUS MIXTURES OF WATERS FROM FORMATIONS A and B. IT CAN BE SEEN THAT THE ABNORMAL PATTERN IN WELL #1 RESULTS FROM A MIXTURE OF APPROXIMATELY 25% A and 75% B.
PATTERN OF WELL #1 AFTER WORKOVER
Na 100
Ca 10
Mg 10
Fe 10
Cl 100
HCO3 10
SO4 10
CO3 10
SCALE (MEQ. PER LITER)

FIG. 7 — DETECTION OF FOREIGN WATER AND DETERMINATION OF ITS SOURCE.

Technical Note 93——

A NOTE ON THE INTERRELATIONSHIP BETWEEN WETTING AND NON-WETTING PHASE RELATIVE PERMEABILITY

M. R. J. WYLLIE, MEMBER AIME, GULF RESEARCH AND DEVELOPMENT CO., PITTSBURGH, PA.

In a recent publication[1] wetting phase relative permeability was expressed as:

$$K_{rw} = \frac{1}{I S_w^2} \frac{\int_0^{S_w} dS_w/P_c^2}{\int_0^{1.0} dS_w/P_c^2} \quad . \quad . \quad . \quad (1)$$

and it was stated that a similar expression applied, *mutatis mutandis*, to non-wetting phase relative permeability; *i.e.*,

$$K_{rnw} = \frac{1}{I_N S_o^2} \frac{\int_{S_w}^{1.0} dS_w/P_c^2}{\int_0^{1.0} dS_w/P_c^2} \quad . \quad . \quad . \quad . \quad (2)$$

In Equations (1) and (2), S_w and S_o are respectively the wetting and non-wetting phase saturations as a fraction of the pore volume; P_c is the capillary pressure; I, the wetting phase electrical resistivity index; I_N, the analogous non-wetting phase electrical resistivity index and K_{rw} and K_{rnw}, the wetting and non-wetting phase relative permeabilities.

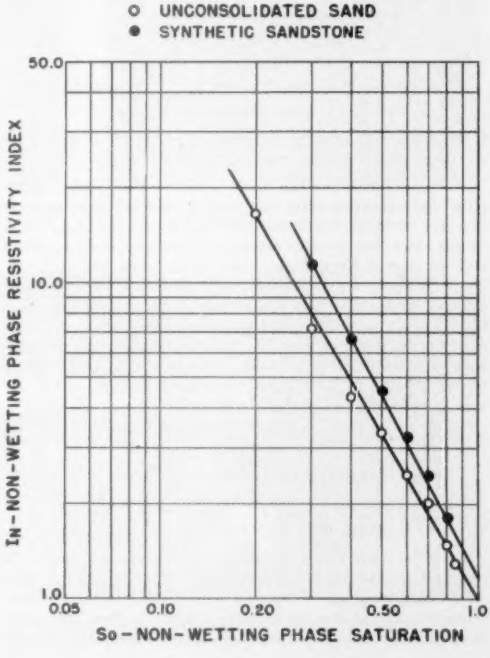
$$\text{But, } \int_0^{1.0} dS_w/P_c^2 = \int_0^{S_w} dS_w/P_c^2 + \int_{S_w}^{1.0} dS_w/P_c^2$$

and from this equality it follows that:

$$K_{rnw} = \frac{1}{I_N^2 S_o^2} [1 - K_{rw} I S_w^2] \quad . \quad . \quad . \quad (3)$$

Equation (3) is interesting because it expresses the non-wetting phase relative permeability of a porous medium at any saturation as a function of the wetting phase relative permeability at that saturation, the saturation itself and parameters which bear directly on the distribution within the pores of the non-wetting and wetting phase fluid networks. It is thus inherently plausible.

Equation (3) is not readily checked against experimental data since few reliable relative permeability figures have appeared in the literature; also no published information exists on the probable relationship between I_N and S_o. However, if the K_{rw} and K_{rnw} figures of Leverett[2] for unconsolidated sands are used in conjunction with the relationship $I = S_w^{-2}$ for sands of this type, it is possible for Equation (3) to compute I_N as a function of S_o. The results are shown in the accompanying figure and it will be seen that $I_N = S_o^{-1.72}$. A synthetic sandstone for which Muskat[3] quotes relative permeability data, also gives a straight line plot between I_N and S_o if $I = S_w^{-1.8}$ is assumed. (A resistivity index exponent of 1.8 appears to be the best average for consolidated porous media.) The slope of the $I_N - S_o$ plot is here −1.87, but the non-wetting phase resistivity index is 1.2 at $S_o = 1.0$, and not unity as would be expected. Whether this difference represents experimental error or is of deeper theoretical significance is not yet clear.



REFERENCES

1. Wyllie, M. R. J., and Spangler, M. B.: "The Application of Electrical Resistivity Measurements to the Problem of Fluid Flow in Porous Media." A.A.P.G., St. Louis (April, 1951).
2. Leverett, M. C.: *Trans.* AIME (1939) **132**, 149.
3. Muskat, M.: *Physical Principles of Oil Production.* McGraw-Hill Book Co., New York (1949), 293. ★ ★ ★

Abstracts of West Coast Fall Meeting Papers

Here are abstracts of five papers to be presented at the West Coast Fall Meeting in Los Angeles Oct. 25-26. Six other abstracts were published in the September issue. The remaining three abstracts were not available in time for publicaion.

156-G
Improved Multiphase Flow Studies Employing Radioactive Tracers

V. A. Josendal, B. B. Sandiford and J. W. Wilson, Union Oil Co. of California, Brea, Calif.

Two radioactive tracers have been tested as a means of determining core saturation in multiphase flow studies. Cesium^{136} chloride was tried as a water-phase tracer, but complications in its use in low permeability cores resulted from sorption of cesium by the core or water-wet pads. Iodo^{131} benzene proved very satisfactory as an oil-phase tracer. The synthesis of iodobenzene from the sodium iodide as received from Oak Ridge is simple and direct. The tracer is insoluble in water and there was no evidence of sorption by any of the core materials used. Use of the method to determine saturation profiles during capillary and dynamic desaturations and relative permeability measurements on oil-water and oil-gas systems is described. Comparisons of the dynamic and capillary methods of relative permeability determination were made using the tracer to check core saturation and saturation distribution. Other experiments are also described in which mobility of the oil phase at various saturations was measured by displacing labeled oil by flowing inactive oil. Similar experiments were made using water labeled with cesium^{136}.

158-G
Drilling Fluid Filter Loss at High Temperatures and Pressures

F. W. Schremp and V. L. Johnson, California Research Corp., La Habra, Calif.

This paper discusses the results obtained from high temperature, high pressure filter loss studies in which field samples of clay-water, emulsion, and oil base fluids were used. The results show that in some instances premium priced emulsion and oil base drilling fluids break down when they are subjected to high temperatures and high pressures. These failures are not predicted by low temperature, low pressure filter loss tests. Failure to predict fluid breakdown emphasizes the danger of using standard filter loss tests to compare the performance of different drilling fluids. Apparatus is described which proved to be satisfactory for evaluating filter loss behavior over a wide range of temperatures and pressures.

161-G
The Quantitative Aspects of Electric Log Interpretation

J. E. Walstrom, Standard Oil Co. of Calif.

While intensive research continues to promote a more complete understanding of the potential and resistivity measurements that comprise the electric log, it is believed that consideration should also be given to translating these numerous findings into a coordinated body of facts designed for the petroleum engineer and geologist. Although provision must be made through publication for a ready exchange of theoretical concepts, it is also necessary to provide reviews and appraisals of these new and untried concepts from the operating standpoint so that an economic and practical application may be realized concurrently with the theoretical progress. With these basic premises as a guide, the author reviews the present state of electric log interpretation.

The paper is directed not so much to the logging or research specialist as to the petroleum engineer and geologist to whom the electric log is only one of the many tools which he employs. Frequently, these persons do not have the time to follow in detail the many specialized contributions that appear, and as a consequence, are not in a position to place these contributions in proper relation to each other.

The paper reviews the basic steps in making quantitative determinations from the electric log of the amount of oil or gas present in subsurface formations. It also indicates the degree of reliability of these determinations under various conditions.

162-G
Engineering Study of the Cook Ranch Field Shackleford County, Texas

Wallace W. Wilson, Continental Oil Co.

The Cook Ranch Field produces from a very permeable lens of Cook Sand of lower Permian or upper Pennsylvanian age, occurring at an average depth of 1,300 ft. The field was discovered in 1926, and has been operated with low pressure gas injection since July, 1927, one of the first such projects in Texas. Cumulative recovery to December 31, 1950, was 14,701,131 bbl of crude oil, an average of 1,013 bbl per acre-ft of oil section, and 67.8 per cent of the oil originally in place. Analysis of the reservoir performance indicates that gravity drainage has been an important factor in the producing mechanism. The high permeability and uniformity of the reservoir were extremely favorable for this type of operation.

163-G
A Study of the Effect of Viscosity on Oil Recovery by Waterflooding

Martin Felsenthal, Continental Oil Co., and **S. T. Yuster,** UCLA

The effect of varying the oil-water viscosity ratio from 0.034 to 95 on results of waterfloods was studied on a section of natural consolidated sand. The oil saturations at water breakthrough and some of the subordinate phase production were functions of the oil-water viscosity ratios. Oil saturations at water break-through and during subordinate phase production agreed approximately in certain ranges with the saturation predicted from the theory of Buckley and Leverett. This theory has been extended to the prediction of field behavior from laboratory results.

Early this month, some 1,025 members of the Petroleum Branch, AIME, gathered at Oklahoma City for the Mid-Continent Fall Meeting held each October. Even judging from attendance alone, the meeting was considered a great success. But other factors counted more toward that feeling . . . good attendance at technical sessions, quality of the 38 papers given and interest in exhibits. At right is a view of the registration desk on the mezzanine floor of the Biltmore Hotel, headquarters for the meeting. At the Welcoming Luncheon, Assistant Secretary of State George C. McGhee enlightened the engineers on some aspects of the Near East oil situation.

Mid-Continent Fall Meeting Attracts 1,025

Assistant Secretary of State George C. McGhee and J. H. Feld, Oklahoma City Section Chairman, chat before the Welcoming Luncheon. At right, registrants sign in. A fine program attracted the record number of registrations.

At left is a general view of the Welcoming Luncheon held in the Persian Room of the Skirvin Hotel. McGhee's talk on the Near East assured a full house. At right, registrants still pour in at second day's end.

No Wonder it's LUCKY!

Look what you get when you use

LANE WELLS

Radioactivity

WELL LOGGING

You get the most complete down-hole information possible, in either cased or open hole, because of Lane-Wells unique combination of advantages. Accurate depth measurements, of course - - - Lane-Wells precision-engineered measuring system is well-known throughout the oil country. The logging is done by Lane-Wells instruments sensitive to every significant change in the formations, yet so thoroughly standardized that they give highly repeatable curves — and that means accurate, dependable curves. And lastly, in running more than 36,000 radioactivity well logs, Lane-Wells has gained unequalled experience in the operating problems and conditions of almost every active field — an invaluable aid in interpretation, particularly where local conditions may cause unusual curve responses.

Put all these advantages together, and it's no wonder so many operators say they won't complete a well without first using Lane-Wells Radioactivity Well Logging.

Tomorrow's Tools—Today!

Ask Your Lane-Wells Man!

General Offices, Export Office and Plant • 5610 So. Soto St. Los Angeles 58, California

Los Angeles • Houston • Oklahoma City
Lane-Wells Canadian Co. in Canada
Petro-Tech Service Co. in Venezuela

AR-405

DISCUSSION OF THIS AND ALL FOLLOWING TECHNICAL PAPERS IS INVITED
Discussion in writing (3 copies) may be sent to the Editor, *Journal of Petroleum Technology*, 408 Trinity Universal Bldg., Dallas 1, Texas, and will be considered for publication in the Transactions volume *Petroleum Development and Technology*. Discussion will close December 31, 1951. Any discussion offered thereafter should be in the form of a new paper.

REPORT ON THE MAMOU FIELD PRESSURE MAINTENANCE PROJECT

WILLIAM O. CREGO,* MAGNOLIA PETROLEUM CO., HOUSTON, TEX., AND **JAMES M. HENAGAN,** MAGNOLIA PETROLEUM CO., MAMOU, LA., MEMBERS AIME

ABSTRACT

The Mamou Field, located in Evangeline Parish, La., is an elongated anticlinal structure on the downthrown side of a major east-west fault with oil and gas production from the upper part of the Wilcox formation. Two main producing horizons occur at an approximate depth of 11,500 ft and have been designated the Morein sand and the Deshotels sand.

The upper sand (Morein) had an original bottom-hole pressure of 6,788 psig, which is some 1,500 psi above the normal pressure for that depth. Oil production with high gas/oil ratios and fluid analyses giving high shrinkage factors prompted a study of the reservoir in its early stages. The results indicated a closed reservoir producing under solution gas drive with low expected ultimate oil recovery.

The early study of the Wilcox formation and its contained hydrocarbons resulted in the presentation of the data to the Department of Conservation of the State of Louisiana, with suggestions for field rules and a request for permission to inject extraneous water into the Morein sand. The water injection plans eventually led to complete unitization of working and royalty interests, to the construction of a gasoline plant, and to a central tank battery installation for the field. Deshotels sand wells were reworked to the Morein sand, and the water injection system was installed and ready for continuous operation in the early part of 1949. The injection of water was started in time to arrest the bottom-hole pressure decline at or near the bubble-point pressure. This injection was calculated to increase the ultimate recovery and to conserve natural resources. Pressure maintenance, the extraction of LPG products, and the sale of residue gas (early 1950) represent an attempt to produce an oil field with utmost efficiency.

INTRODUCTION

The two principal Wilcox oil horizons in the Mamou Field are the Morein sand and the Deshotels sand, occurring at 11,500 ft and 11,700 ft subsea, respectively. Minor oil production has been encountered in Morein stringer sands. (Fig. 1.)

This paper deals only with the Morein sand, which is blanket over the Mamou Field. It is, however, segmented by the northwest-southeast "E" fault as shown in Fig. 2. The west segment is the area involved in the water injection pressure maintenance program. To date the east segment has operated largely under the influence of a strong water drive.

The paper presents (1) a brief history of field development, (2) a resumé of reservoir conditions which led to the decision to inject extraneous salt water into the principal producing horizon, and (3) a summary of reservoir analysis and performance.

FIELD DEVELOPMENT

The Mamou Field is located in Evangeline Parish, La. The discovery well (J. B. Morein No. 1, now Unit No. 5) was completed in December, 1945, after penetrating 200 ft into the Wilcox formation. Initial production from the Morein

*Now with the Tennessee Gas and Transmission Co., Houston, Tex.

Manuscript received in the Petroleum Branch office May 26, 1950. Paper presented at the meeting of the Delta Section, AIME, in New Orleans, La., Jan. 9, 1950.

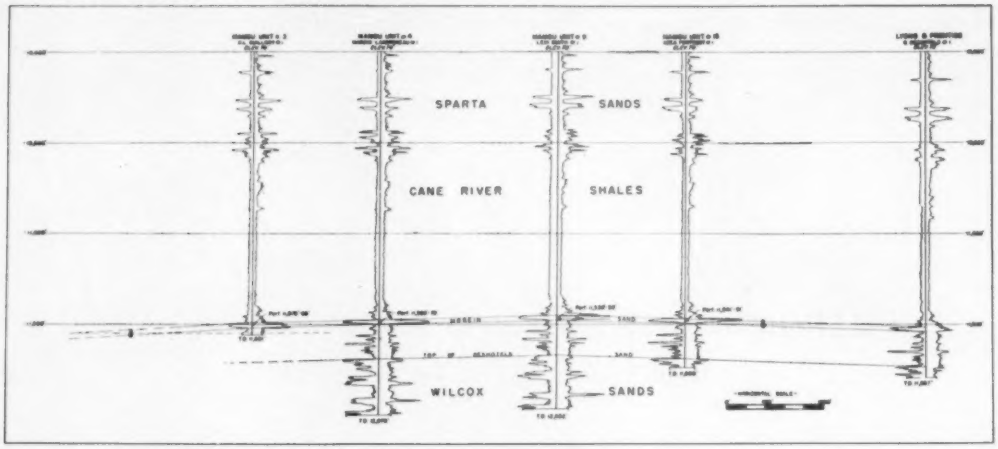


FIG. 1 — NORTH-SOUTH ELECTRIC LOG CROSS-SECTION, MAMOU FIELD.

sand was 208 B/D of pipe line oil through an 8/64-in choke with a tubing pressure of 3,950 psig.

Following the successful completion of the discovery well, preliminary tests were made to evaluate the productivity of the reservoir. Evidence on the character of the reservoir which had to be considered to protect development costs was: (1) a 21-ft sand at 11,500 ft with an average permeability of about 51 md, (2) the possibility of a saturated fluid in a reservoir operating under volumetric depletion, (3) a fluid at or near the critical state, and (4) a solution gas/oil ratio of approximately 4,000 cu ft per bbl of stock tank oil. Expected recovery under these conditions would be very low.

The production rate of 260 B/D of oil was reduced to 150 bbl to conserve reservoir energy while a more thorough investigation was begun in order to predict profitable development of the Morein sand.

By August, 1946, a total of eight wells had penetrated the Morein sand within one mile of the discovery well. Three of these wells were completed in the Morein sand; two were producing from the Deshotels sand; and the remaining three wells were in the process of testing. At the end of 1946 the reservoir pressure was declining at the rate of one lb for each 350 bbl of stock tank oil produced. All available data indicated that the recoverable oil would not warrant continuation of the 40-acre development pattern under which the field was being drilled.

The most efficient recovery mechanism was assumed to be displacement by water while maintaining the reservoir pressure above the saturation point. Eighty-acre drilling units were considered to be an efficient as well as economical pattern if the reservoir could be properly controlled. Field development continued with 80-acre spacing while complete reservoir data were presented to the Department of Conservation of Louisiana requesting field rules. A voluntary unitization agreement between the principal operator and a majority of the royalty owners was presented with a request for the formation of the Mamou Unit, equities to be distributed on the basis of acre-feet of oil productive sand underlying individual leases. Wells in the Deshotels sand were to be recompleted in the Morein sand to complete the spacing pattern; the operator was to construct a natural gasoline plant with the royalty owners sharing in 100 per cent of plant products; and a pilot water injection system was to be initiated to determine the feasibility of pressure maintenance. The field rules with 80-acre spacing and the establishment of the Mamou unit were approved. Permission was granted to inject extraneous water into the Morein reservoir experimentally.

In 1947, the four Deshotels sand wells were reworked to the Morein sand to complete the drainage pattern for the pressure maintenance program in that reservoir. A total of 25 wells was drilled in the Mamou Field; 19 were oil producers and six were dry holes. Following the State order to form the Mamou Unit, work was commenced on a central tank battery, a natural gasoline plant, and a pilot water injection system.

WATER INJECTION SYSTEM

After laboratory tests indicated a reduction in permeability in the Morein sand by use of fresh water, a high pressure, salt water injection system was designed. A dry hole on the north side of the field was selected for injection, and continuous water injection was begun in February, 1949.

Extraneous salt water is supplied by another dry hole perforated in a sand at a depth of 2,300 ft. A deep-well centrifugal pump at a depth of 600 ft lifts the water and delivers it about three-fourths of a mile to the injection well. At the injection station the mixed salt water from the supply well and the salt water produced from the Morein sand is filtered. After passing through a two-element, sand-packed filter, the water goes into a volume tank before it is metered into the suction line of the injection pump. The system is kept under

low gas pressure to keep air excluded. This closed system has eliminated the need for chemical treatment.

An inverted, quintuplex pump forces the water into the injection well. In the solid-steel fluid end the water pressure is raised to 3,200 psig. The first plungers used in the pump were plated with porous-chrome steel. During operation, the packing glands are lubricated by castor oil. The porous-chrome plungers were satisfactory but were abrasive to the packing at the high pressure. By substituting solid-ring for the split-ring V-type packing much of the wear was eliminated. Porcelain plungers were tried, but some failures of the plungers have occurred. Power for the injection pump is furnished by two 300 hp engines which are connected to the pump by a 3.2 reduction gear.

At the sand face, 11,631 ft deep, there is 3,600 psi differential between the well bore and the average reservoir pressure while the water is being injected at a rate of 2,000 B/D.

RESERVOIR ANALYSIS AND PERFORMANCE

Reservoir Characteristics — Morein Sand

The results of porosity determinations show a weighted average porosity of 19.7 per cent for 197 ft of cores in the Morein sand and a weighted average permeability of 51 md.

The interstitial water saturation of 34.7 per cent was obtained from cores taken with a water base mud and corrected for infiltration of water from the drilling fluid for 104 ft cored west of the "E" fault. Again the interstitial water was checked by the capillary-pressure method using 11 cores that varied in permeability from 3.4 to 149 md. The resulting curves of interstital water *vs* height above the water table were used with available permeability data to obtain an average interstitial water saturation for the oil zone of 35 per cent.

Placing of Water-Oil Contacts

Data were assembled to determine the boundaries of the oil zone in the Morein sand. The water-oil contact for the south and west flanks was placed mainly from data obtained on the Unit No. 12 well. The sand was perforated in the top two ft of permeable section from 11,487 to 11,489 ft subsea to make a water-free producer. Early appearance of water production from the well placed the perforations near the water-oil contact. Completion of Unit No. 15 through perforations from 11,484 to 11,494 ft subsea tested no water, but the well started making water during the first month of production. From Wells No. 14 and 16, the water-oil contact was placed at 11,500 ft subsea for the west and south flanks of the west segment (See Fig. 2).

The La Haye Brothers No. 1 well cut the water-oil contact as shown by core analysis report and by a slight show of oil on a drill stem test from 11,550 to 11,555 ft subsea. Unit No. 3 with perforations from 11,496 to 11,506 ft subsea, 13 ft lower than Unit No. 13 on the south flank, has produced over

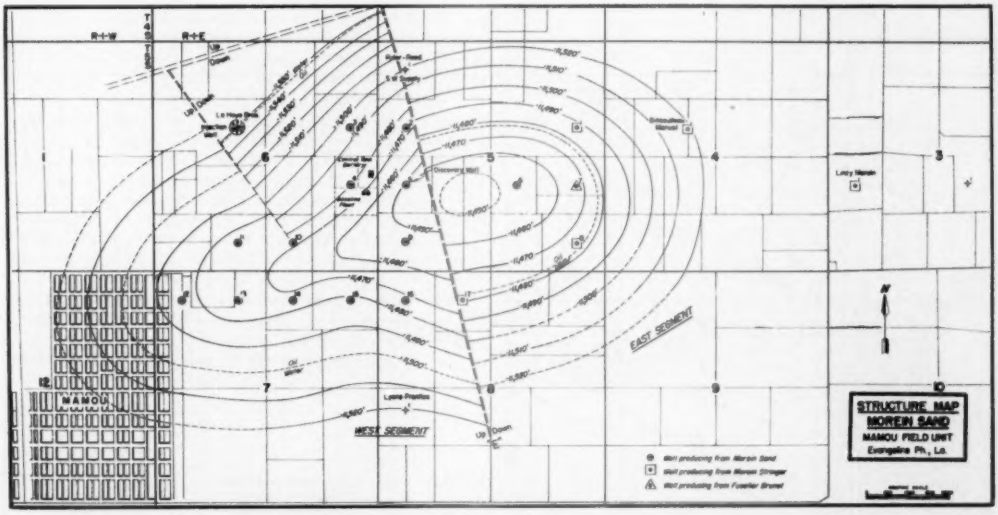


FIG. 2 — STRUCTURE MAP, MOREIN SAND, MAMOU FIELD UNIT.

130,000 bbl of oil with no water. The water-oil contact was placed at 11,549 ft subsea in an area that is shut off by effective barriers to the north, east, and west.

Reservoir Volume, Temperatures and Pressures

The estimated reservoir volume for the pressure maintenance area is 14,917 oil acre-ft, based on 963 surface acres and an average sand thickness of 15.5 ft.

All bottom-hole pressure tests in the Morein reservoir have been corrected to 230°F and to the datum of 11,428 ft subsea. A study of the early bottom-hole pressure tests and calibrations indicated the initial bottom-hole pressure for the Morein sand of 6,788 psig measured on Jan. 2, 1946, to be correct. Sufficient pressures were available to form and follow the pressure trends in the early life of the field. Since June, 1947, there have been pressure surveys every three months to give excellent reservoir pressure information. The bottom-hole pressures were adjusted to survey dates and arithmetically averaged, since the well spacing allowed each well approximately the same area.

From prepared isobaric maps, the changes in the pressure pattern were followed as conditions in the reservoir changed. As would be expected, the greatest pressure decline occurred in the area where the first wells were completed on the highest part of the structure. The maps showed a continual movement of the low pressure area from the original area toward the north. Although a greater number of wells were drilled on the south flank, the low pressure area moved to the most northerly producing part of the field.

Following the injection of water, the pressure pattern shifted as shown in Fig. 3, indicating an exertion of pressure inward from all directions except along the "E" fault. The isobaric pattern rapidly improved and began to conform to the structural contours.

On December 22, 1948, the reservoir pressure in the Morein sand west of the "E" fault had declined 1,705 psi to 5,083 psig while 801,312 bbl of stock tank oil had been produced. This is a production of 471 bbl per psi pressure decline (Fig. 4).

Although data acquired indicated some water drive in the southern flank, continuous water injection was commenced on Feb. 16, 1949, to arrest the pressure decline. The decline continued but was gradually reduced until June, 1949, when a pressure of 4,967 psig was noted; thereafter, the water injection has shown the desired effect on the pressure.

Reservoir Production Data

Through September, 1948, all production went into separate tankage for each well. Since the installation of a central tank battery in October and November, 1948, production of oil, gas and water has been broken down on the basis of monthly tests.

The cumulative water production for the Morein sand west of the "E" fault through Aug. 18, 1949, was approximately 51,000 bbl or an average water production of 4.94 per cent. At that time, Units No. 12, 14, 15 and 16 in the pressure maintenance area were producing over 50 per cent water. Cumulative production of oil, gas, and water to January 1, 1951, is shown in Fig. 4.

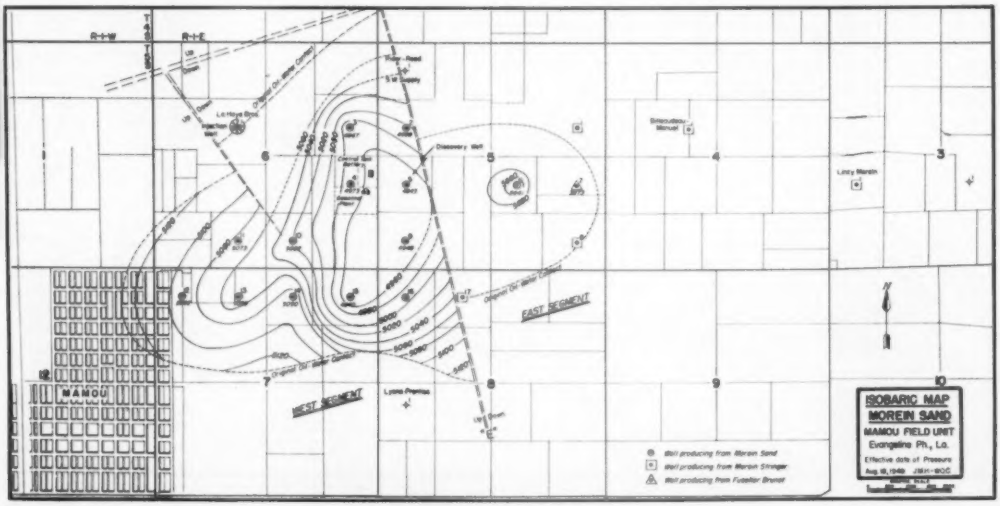


FIG. 3 — ISOBARIC MAP, MOREIN SAND, MAMOU FIELD UNIT.

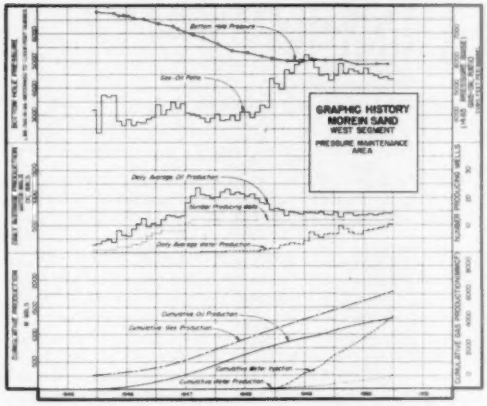


FIG. 4 — GRAPHIC HISTORY, MOREIN SAND, WEST SEGMENT, PRESSURE MAINTENANCE AREA.

Reservoir Fluid Analyses

Summaries of the results of the fluid analyses of two subsurface samples and two surface recombination samples made on the Morein reservoir are shown in Table I. The fluid behavior of two samples from the Unit No. 3 well (O. L. Guillory No. 1, lowest structural position) producing from the Morein sand has been determined. One was a subsurface sample and the other was a recombination sample. The two analyses were performed independently by different laboratories. The bubble points of 4,527 psig and 4,540 psig checked very closely, indicating the reservoir fluid to be undersaturated at reservoir conditions. As the gas/oil ratio by flash liberation checked closely with the producing gas/oil ratio for this well (3,000 cu ft per bbl of stock tank oil), it is believed that these two analyses are fairly representative of the shrinkage and gas/oil ratio behavior of the fluids being produced from this well and wells on a similar structural position.

The fluid behavior of two samples from the discovery well (Unit No. 5), which is producing from the highest structural position, was determined. One was a subsurface sample and the other was a recombination sample. These samples were also analyzed independently by different laboratories. The difference in producing gas/oil ratio flashed to approximately 300 psig was only 40 cu ft per bbl of stock tank oil (3,950 cu ft per bbl of stock tank oil for the bottom-hole sample compared to 3,990 cu ft per bbl of stock tank oil for the recombination sample), which indicated representative samples of fluids from the well. These analyses are fairly representative of the shrinkage and gas/oil ratio behavior of the fluid in the reservoir on the higher part of the structure (Fig. 5).

Water Influx

In October, 1949, the water influx into the reservoir through each of the nine pressure survey periods (through Aug. 18, 1949) was calculated by material balance equations.

The volumetric balance calculations indicated that the reservoir had been produced through a combination of water drive by edge-water encroachment and expansion of reservoir fluid supplemented by water injection. Through the last survey date, Aug. 18, 1949, the energy for the production of oil and maintenance of the reservoir pressure was derived 55 per cent from water influx into the reservoir, 36 per cent from the expansion of the reservoir fluid, and 9 per cent from the injection of water.

The cumulative water production of approximately 51,000 bbl (1.39 per cent of the total reservoir voidage by oil, gas and water production) and wells producing water were consistent with the calculated influx and reservoir volume data. The calculated water influx of 2,009,000 bbl, which has been primarily on the south and southwest flanks, would cause a rise of about 8.6 ft in the water-oil contact if the water advanced uniformly and if the resulting residual oil saturation were 20 per cent of the total pore space. This rise from the original water-oil contact of 11,500 ft subsea would place the contact near the top of the perforations in Unit No. 12, and in August, 1949, this well was producing over 70 per cent water. This rise would also place the contact above the bottom perforations in Unit No. 13 and a rise to nearly the center of the perforated interval in Unit No. 15 with the two wells producing 16 and 57 per cent water, respectively. Considering the accuracy of the depth measurements below 11,000 ft, the aforesaid production of water checks the rise in the water-oil contact rather closely.

Pressure Maintenance

The average rate of pressure decline was approximately 47 psi per month from the original pressure to the time of injection. Three months after injection was initiated, the pressure decline was nearly arrested with the pressure rising slightly after that time.

Although on Aug. 18, 1949, the injection of water had accounted for only nine per cent of the energy for the cumu-

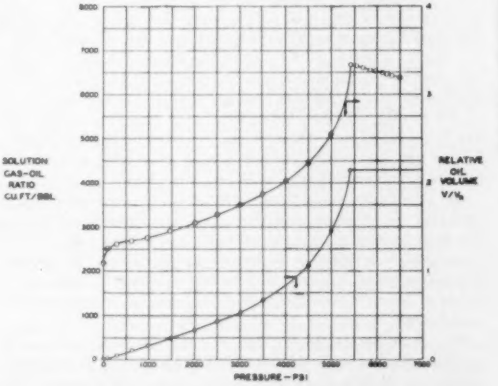


FIG. 5 — SOLUTION GAS DURING DIFFERENTIAL LIBERATION AND RELATIVE OIL VOLUME VS. PRESSURE, J. B. MOREIN NO. 1 — MOREIN SAND, MAMOU FIELD, JULY 26, 1946.

Table I — Fluid Behavior Analysis Summary — J. B. Morein-Wilcox Reservoir

Mamou Field — Evangeline Parish, La.

	O. L. Guillory No. 1 (Surface Recombination)	O. L. Guillory No. 1 (Bottom Hole)	J. B. Morein No. 1 (Surface Recombination)	J. B. Morein No. 1 (Bottom Hole)
Reservoir Temperature, °F	230	230	230	230
Bubble-Point Pressure, psig @ 230°F	4512	4540	5415	6265
Formation Volume Factor, Vr/Vt by diff. lib. @ Res. Temp.	....	3.05	3.14	2.48
Formation Volume Factor, Vr/Vt by flash lib. to 250 psig	2.84*	2.98	2.95	2.42
Formation Volume Factor, Vr/Vt by flash lib. to zero psig	....	3.58	3.80	2.68
Solution Gas/Oil Ratio, CFPB by diff. lib. @ Res. Temp.	....	3734	4296	4160
Solution Gas/Oil Ratio, CFPB by flash lib. to 250 PSIG	2800*	3320	3934	3990*
Gas/Oil Ratio produced by well at time of sampling, CFPB	2794	....	3918	3950
Solution Gas/Oil Ratio, CFPB by flash lib. to zero psig	....	4149	4721	4660
Residual ST Oil gvty. by flash lib. to 250 psig, API at 60°F	49.4**	46.7	44.5	....
Specific gvty. of Sep. Gas flashed to zero psig sep. press.	....	1.027	0.897	0.725
Oil viscosity, cp. at bubble-point press. and Res. Temp.	....	0.177	0.174	0.25
Avg. Compress. at Res. Temp. in the bubble-point region vol/vol psi	70.5×10^{-6}	54.5×10^{-6}	43.8×10^{-6}	22.4×10^{-6}
Thermal expansion of Sat. Oil @ 7,500 psig, % per °F	0.185***	0.0923	0.0968	0.0531
Specific Volume @ Bubble-Point Pressure and Res. Temp.	....	0.03285	0.03494	0.0265

* Based on preliminary report and separator pressure between 280 and 300 psig.
** Gravity of stock tank oil produced when flashed to 282 psig separator pressure.
*** At 6,800 psig.

NOTE: Vr/Vt refers to the number of barrels of fluid at original reservoir conditions required to produce one barrel of stock tank liquid. CFPB refers to cu ft of separator gas at 15.025 psia and 60°F per bbl of stock tank liquid at 60°F.

lative expulsion of reservoir fluids; the last survey period from June 8, 1949, to Aug. 18, 1949, shows that 46 per cent of the energy was furnished by water injection. As the pressure was held nearly constant, the water injection and edge-water encroachment were the only factors that were considered to furnish energy to produce the reservoir fluids. Thus, with an injection slightly in excess of 2,000 B/D, a balance between water encroachment and water injection was established. This balance should keep the reservoir fluids from any shifting which could have resulted by encroachment of water from the south and west only.

Predictions

It was assumed in making the predictions (1) that the vertical rise in the water-oil contact was equal throughout the areal extent of each section, (2) that the efficiency factor for the area west of the "E" fau't would be 65 per cent, (3) that the wells will be shut-in when the water-oil contact reaches the top perforations for the well, (4) that the pressure of 5,000 psig will be maintained, and (5) that energy for expulsion of reservoir fluids would be furnished approximately 50 per cent by water injection (north side) and 50 per cent by water encroachment (south and west flanks).

An injection rate of 2,000 B/D at the present time should maintain the reservoir pressure at or near 5,000 psig. As the water-oil contact rises and the wells go to water, the rate of water injection will be decreased proportionally to balance the decrease in the rate of reservoir voidage to maintain a balance between injected water and natural edge-water encroachment.

The reservoir producing rate for the Morein sand in the pressure maintenance area (west segment) will decrease as individual wells are shut in due to water production. The wells along the southern flank of the field are steadily going to higher percentages of water production; however, the rates for each of the other wells should remain near the present level until such time as they are curtailed by encroaching water.

Without water injection the ultimate recovery from the west segment of the Morein sand could be increased approximately 30 per cent by a decrease in reservoir withdrawal rates. This would take full advantage of the natural water drive on the south but would increase the time needed for ultimate recovery by approximately 100 per cent. When consideration is given to reservoir withdrawal reductions, it must be pointed out that an absence of a natural water drive from the north would not allow the area on the north to be swept by water.

The ultimate recovery from the west segment with high pressure salt water injection will be increased approximately 66 per cent over the recovery possible without pressure maintenance and without reservoir withdrawal reduction. Likewise, the ultimate recovery with pressure maintenance will be increased by 28 per cent over recovery by primary production with a reservoir withdrawal decrease, and the time needed for the recovery will be reduced by nearly 50 per cent.

ACKNOWLEDGMENTS

We wish to acknowledge the help and cooperation received from the Producing, Land, Natural Gas, Geological and Petroleum Engineering Departments of the Magnolia Petroleum Co. in obtaining data incorporated in this paper. Appreciation is expressed to the management of the Magnolia Petroleum Co. for permission to publish this paper.

REFERENCE

"A Study of the Mamou Field," Petroleum Engineering Dept., Magnolia Petroleum Co., Dec. 1, 1949 (unpublished).

★ ★ ★

INTERSTITIAL WATER DETERMINATION BY AN EVAPORATION METHOD

E. S. MESSER, CONTINENTAL OIL CO., PONCA CITY, OKLA., MEMBER AIME

ABSTRACT

A knowledge of the magnitude of the irreducible interstitial water in a porous medium is so important to petroleum engineering that its determination has become routine in core analyses.

The method of determination, being a production problem, should encompass the basic requirements of simplicity in technique and calculations, with reproducible results obtainable in a short interval of time. The results of the evaluation tests outlined in this report indicate that the evaporation method for determining the irreducible water is a technique which meets the requirements.

The procedure consists, as the name implies, of permitting the saturant in the pore spaces to evaporate until only an irreducible volume remains. The determination of this volume can be made either graphically or by a mathematical comparison of fluid flows; the time required for each determination being dependent on the fluid used.

When fluids other than those having reservoir characteristics were used, a volume factor had to be calculated which was based on the relative volume of various liquids adsorbed on grain surfaces and retained in pores. This factor made possible the calculation of an irreducible water volume when more volatile fluids such as toluene and benzene were used as the saturants.

Also presented is the theoretical discussion necessary for the calculation of the capillary pressure as determined from the evaporation curve. A comparison is made between the calculated values and those obtained by experimental means.

INTRODUCTION

In all geological formations there exists, in the pore spaces of the rock structure, water that is held in a state of equilibrium between capillary and hydrostatic forces. "Interstitial water" is the term given to this water and is defined as that water coexisting in the pore space with the oil prior to exploitation. The term "connate water" has often been used synonymously with this term; however, this can be true only by a specific definition since, geologically, it means the water in place at the time the rock structure was formed.

The quantity of the interstitial water is a variable factor in any formation, since it depends on the hydrostatic forces present in any multiple-phase system. These forces may become unbalanced by the introduction of an extraneous force such as the raising or lowering of the "water table" or the migration of oil into a water-filled formation. Any unbalanced force results in a change in the interstitial water.

There exists, however, an irreducible interstitial water, for a particular sand, that is the fraction of the pore space occupied by water when the capillary pressure at the particular point in question is at an equilibrium with the hydrostatic head of the oil sand in the reservoir. For this discussion the term "irreducible water saturation" will be used in place of "irreducible interstitial water saturation" for the sake of brevity; however, they are understood to be identical.

A great amount of work has been devoted to the theory and methods for studying the irreducible water saturation and its related capillary pressure. As a result of the publications of Leverett;[1] Hassler, Brunner and Deahl;[2] Calhoun and Lewis;[3] and others, the role of capillary pressure studies is being accepted by the industry as a tool for studying subsurface phenomena. Many techniques have been developed and published for determining the capillary pressure and irreducible water. In general, these techniques may be grouped into three classifications. One of the first was the capillary pressure method described by Leverett[4] and expanded by Bruce and Welge.[5] The experimental results were compared with water saturation of cores obtained using oil-base mud. Thornton and Marshall[6] compared the irreducible water saturation of core samples determined by the capillary pressure method and by salinity and reported good agreement between the two methods.

The second classification for determining the irreducible water and capillary pressure may be referred to as the "centrifugal force method." The general technique is similar to the capillary pressure method except that the force driving the reservoir fluid from the sample is of a centrifugal nature. A complete description of this method was presented by J. J. McCullough and F. W. Albaugh.[6]

A process, the reverse of the capillary pressure method, was presented by W. R. Purcell.[7] Mercury under pressure is driven into the pores of the rock and the saturation of the core determined at each applied pressure. The resulting capillary pressure curve is used to evaluate the irreducible water saturation.

The techniques mentioned are singular in their approach to the irreducible water saturation. In all cases, an external force was applied to the core. The forces employed in the evaporation method are the vapor pressure of the liquid causing evaporation, the kinetic diffusion forces, adsorptive forces and, to a lesser degree, the viscous forces resisting flow to the surface.

The basic definition of irreducible water is that water held in a state of equilibrium between capillary and hydrostatic forces. This water has been described by previous investigators as being held in the microcapillaries too small to support fluid flow. Actually, this fluid volume is made up of the water in the microcapillaries and as a film adhering to the surface of the crystals. All capillaries, therefore, possess some liquid as a film, the thickness of the film being dependent on the properties of the fluid and solid. A discussion of experiments with references pertaining to the measurement of this immobile layer next to the solid surface can be found in the text by J. J. Bikerman.[8] Eversole and Lahr calculated the thickness of this layer to be in the order of 10^{-7} to 10^{-6} cm for aqueous solutions and glass. Between two quartz surfaces they found the thickness to be 2×10^{-6} cm. The work of Volkova, on the capillary movement of water and toluene in quartz grains, indicated the thickness of the immobile layers to be near 10^{-6} cm. Since any measurement is an average value, it is easy to understand that an absolute value would depend on the roughness of the surfaces involved and the complexity of the system. A calculated effective pore radius of 2×10^{-5} cm is obtained at the irreducible saturation of a porous media in a water-air system when a capillary pressure of 100 psi is applied. Since the separation of the sand grains is of the same approximate magnitude as the immobile layer,

[1] References given at end of paper.

Manuscript received in the office of the Petroleum Branch Aug. 17, 1950. Paper presented at the Fall Meeting of the Petroleum Branch in New Orleans, La., Oct. 4-6, 1950.

it may be probable that the major portion of the irreducible volume can be classified as this multilayer film.

Consider then a core sample that has been saturated with a liquid which wets the solid surfaces and exhibits an approximate zero angle of contact. At the beginning of the evaporation process the fluid surface in the 100 per cent saturated core may be considered nearly flat, and the rate of evaporation is a function of the exposed area of the core surface, the velocity and humidity of the drying media. As evaporation of the fluid proceeds, there will be a migration of the fluid front to the interior section of the core and capillaries of smaller radii, resulting in a reduction in the saturated vapor pressure. Due to the gradual decrease of the vapor pressure, and increase in complex flow path, the rate will decrease as the concentration decreases. The larger pores will be the first to be emptied, and if the process could be brought to an equilibrium at a particular saturation, capillaries of higher meniscus curvature by virtue of the smaller pore diameter than the equilibrium vapor pressure indicated would be completely saturated with the liquid and the larger pores would be lined with a continuous multilayer film. This film would be thick at the concave meniscus and would make a zero angle of contact with the fluid surface. The thickness of the multilayer would decrease as the distance to the outer core surface increased.

The actual mechanism of flow during desaturation is complex; however, it may be considered mainly as vapor migration by evaporation and recondensation on the multilayer film, resulting in a net loss by vapor diffusion to the drying air stream at the exterior of the sample. At the point of irreducible saturation, when the microcapillaries remain completely saturated, further migration of the meniscus results in only a small change in the adsorbed volume and the net loss in weight would be due to the evaporation of the multilayer film lining the larger capillaries. This rate of desaturation would be uniform for a short interval of time due to the approximate constant area and diffusion path.

As the evaporation proceeds, the constant rate of desaturation will decrease as the film lining the pores becomes less thick and the forces associated with the liquid-solid interface become more pronounced. The change in the rate of desaturation after the irreducible saturation has been reached will depend on the liquid and solid surface characteristics.

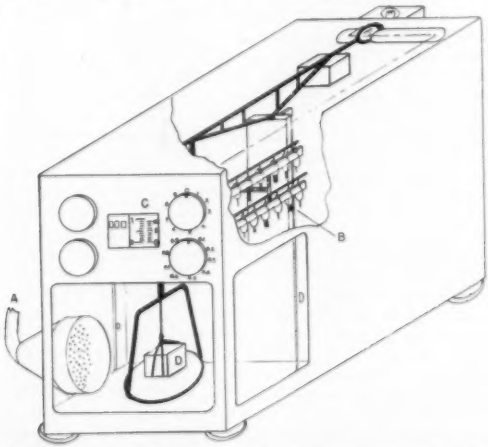


FIG. 1 — SCHEMATIC DRAWING OF COMMERCIALLY-MADE AUTOMATIC BALANCE.

After the initial saturation and the meniscus has receded to the internal section of the core, vapors must diffuse through the pore space of the substance before entering the atmosphere for a second diffusion action. Edward Ledoux,[8] in his text on vapor adsorption, describes the desorption efficiency in the case of an adsorbed liquid inside the adsorbent. For low rates of evaporation, the coefficient of diffusion friction or the change in vapor pressure with distance of diffusion inside the adsorbent is proportional to the mass of flow of vapor and a constant which is characteristic of the structure of the adsorbent. When this diffusing amount reaches the outer surfaces of the adsorbent it will be transferred to the air where the vapor pressure is P^1. The general equation combining the two diffusion processes, inside the adsorbent and from the surface to the air, is then:

$$Qm = K(P_v - P^1) \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

For practical purposes, with dry air blowing across the face of the sample, its vapor pressure P^1, in the atmosphere at a unit distance above the sample, will be small and may be neglected.

In Equation (1), K is the overall coefficient of vapor transfer for desorption and is essentially a combination of the coefficient of diffusion per unit distance inside the adsorbent and the coefficient of vapor transfer outside the adsorbent. By definition, K is the amount of vapor transferred per unit time, per unit area by a unit vapor pressure difference. The units are therefore $gm\ sec^{-1}\ cm^{-2}\ \triangle P^{-1}$ and the absolute value for a core can be determined only through experimental means.

Before proceeding further with a study of Qm and K, it is necessary to determine the variation of P_v in the porous media during desaturation. If the pressure on the liquid in the pores is exerted by virtue of the curvature of the meniscus, the relationship between the equilibrium vapor pressure P_v over the concave meniscus of a wetting liquid to the vapor pressure P_o over the plane surface may be represented as a function of the radii of curvature by:

$$Ln \frac{P_o}{P_v} = \frac{2\delta M}{\rho R T r} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (2)$$

where δ is the surface tension of the liquid, M the molecular weight of the vapor, R the gas constant, T the absolute temperature, and r the radius of curvature of the meniscus. If the pores are assumed circular, with a zero contact angle between liquid and solid and the adsorbed film negligibly thick, then r is the equivalent pore radius. For water at 20°C, the right-hand side of Equation (2) is $1.07 \times 10^{-7}/r$ and it can be seen that the reduction in vapor pressure due to the capillary curvature is small for pores whose radii are of the order of a few microns. For an average core sample above the irreducible volume, the vapor pressure may be considered constant and the vapor flow varies as the coefficient of vapor transfer.

According to Equation (1) for a particular adsorbent, the mass flow of vapor will remain constant if vapor pressure difference, diffusion area, and liquid characteristics remain constant. A core sample at any saturation below 100 per cent may be considered as consisting of n uniform capillaries of cross sectional area a and volume V_1, completely filled with vapors at an equilibrium vapor pressure. The total volume of vapors V is then $n\ V_1$ which is numerically equal to the pore volume less the liquid volume at saturation S_1. A representative area for diffusion at S_1 is V/L_1, where L_1 is the effective length of the capillary. The total mass vapor flow from the adsorbent is then:

$$Qm = \frac{KV}{L_1} P_v \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (3)$$

Table I — Physical Properties of Test Samples

Core No.	Formation	Pore Volume (cc)	Rock Volume (cc)	Porosity %	Air Permeability (md)
DG18	Sandstone	1.53	3.84	28.5	5085
P57	S. Dolomite	1.36	3.94	25.7	2648
CS3	Dolomite	1.76	4.26	29.2	1099
DG1	Sandstone	1.58	4.15	27.6	814
OG9	Sandstone	1.04	4.82	17.8	539
84Z	Sandstone	1.00	4.59	17.9	295
DG8	Sandstone	1.53	4.39	25.8	204
79C	Sandstone	1.37	5.38	20.2	115
02C	Sandstone	1.08	4.56	19.2	78
31C	Sandstone	1.03	4.57	18.4	55
AS1	Sandstone	1.24	4.44	21.8	37
AV20	Sandstone	.80	4.33	15.6	34
87B	Limestone	1.53	7.24	17.5	19
18C	Limestone	1.03	5.06	16.9	16
AD30	Sandstone	1.05	5.11	14.8	14
88E	Limestone	1.37	5.66	19.5	6.5
CS13	Dolomite	.74	5.45	12.0	6
21C	Limestone	1.10	4.94	18.2	2.3
88T	Sandstone	.96	4.68	17.0	1.9
AV7	S. Dolomite	.51	5.85	8.0	.8

If it is assumed that during desaturation equilibrium conditions are approximately maintained, then the combination of Equations (2) and (3) leads to a general relationship for mass vapor flow in terms of liquid and core characteristics:

$$Qm = \frac{K}{L_1} V P_a \exp.-\frac{2\delta M}{\rho R T r} \quad . \quad . \quad . \quad . \quad . \quad (4)$$

At the saturation representing irreducible volume, the change in V and r is small; K and L_1 remain constant for a short interval of time such that the resulting rate of desaturation remains constant.

As previously stated, desaturation of a core is due to vapor migration by the process of evaporation and recondensation and a film remains on the outer crystals of the core prior to the irreducible volume. The presence of this film was observed by placing a saturated core under a microscope with a stream of dry air passing over the film. In tight formations, there seemed to be periodic drying of the surface; however, it was not continuous as liquid resaturated the crystals. The film existed until irreducible volume was reached; after that, drying occurred.

EXPERIMENTAL PROCEDURE

The evaporation method for determining irreducible water saturation is rapid and, in general, the experimental procedure consists as the name implies of evaporating the fluid from a saturated core until the rate of desaturation first becomes constant for a period of time. The fluid remaining in the core at the beginning of this constant rate represents the irreducible fluid volume.

More specifically, the experimental procedure consists, first, of saturating a clean core with a liquid that forms a zero contact angle with the solid and does not leave a residue when evaporated or cause any chemical reaction with the sample itself. Liquids such as a metal-containing organic compound or its chemical derivative should not be used as they remain deposited in the core sample after the test has been completed. If such a liquid is used, corrections which will be discussed later must be applied to compensate for the deposited weight. Examples of some of the liquids used and found satisfactory are water, toluene, tetrachlorethane, benzene, and n-propyl alcohol.

The liquid-saturated core sample is then placed on the platform of a balance capable of indicating continuous weight change as the fluid evaporates from the pores. A schematic drawing of a commercially-made automatic balance that was used and found satisfactory is shown in Fig. 1. The system is initially in equilibrium, the weight of the saturated core *(D)* being compensated by the removal of weights *(B)* from a suspended bridge fixed to the pan lever system. When the sample changes in weight, as that associated with the evaporation of liquid from the pore spaces, the motion of the balance arm can be observed by a beam of light traveling across a vernier scale *(C)*. By this means the continuous change in sample weight can be observed.

A stream of gas or air from *A*, passing over the sample, speeds the rate of evaporation and reduces the time interval for each test. An air flow of approximately 20 cfm was found satisfactory as it was not sufficient to agitate the balance and cause erroneous readings. During the experiment, weight readings were taken at equal intervals. These, transformed to fluid volume measurements, were plotted as a function of time.

In the first group of tests to evaluate this method, 20 samples from different formations and having different characteristics, shown in Table I, were selected. These samples were saturated with various liquids mentioned and an irreducible liquid volume determined for each sample and liquid according to the theory previously described. Typical desaturation curves for core samples of high and low permeability are shown in Fig. 2 for water, toluene and tetrachlorethane. These curves are characteristic of the solid-liquid system, the irreducible volume being represented by the point where the rate of desaturation becomes approximately constant. In actual laboratory practice, it was not necessary to plot the curves as the irreducible volume could be more accurately determined by a study of the loss in weight per unit time during the test.

Experimental data for the desaturation curve of Core Sample No. 79C is shown in Table II together with the change in volume of the saturant with time. The fluid volume in the core at the point when the rate becomes approximately constant represents the irreducible liquid volume. In the case of Sample No. 79C, for water it would be .221 cc, for tetrachlorethane .251 cc, and for toluene .266 cc. The approximate constant rates are .020 cc per five minutes, .013 cc per five minutes, and .013 cc per minute respectively.

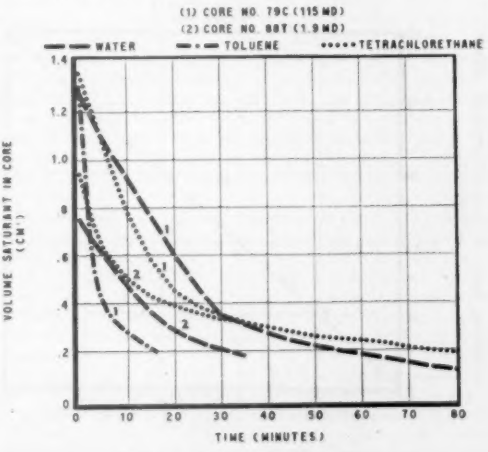


FIG. 2 — PORE FLUID RETENTION.

It can be seen from Table II that the irreducible liquid volumes are different and depend on the liquid used. To calculate the irreducible water saturation, formation water would be the most appropriate to use; however, the depositing of salt in the pores presents another correction to be applied. Distilled water would be the best substitute as it has the same surface tension characteristics. In J. J. Bikerman's text, *Surface Chemistry*,[9] a table is presented from the work of Grinnell Jones on the variation of surface tension of brine with water. For a solution of 25,000 ppm *NaCl*, the ratio of surface tension of the solution to water is 1.00153. The correctness of using water in place of reservoir fluids is further emphasized by the fact that, as a result of the tendency toward free energy of a surface to decrease, the concentration of a solute on the interface may differ from the bulk. If the solute brings about an increase of surface tension as in the case of *NaCl*, its concentration will be less in the surface than in the remainder.

Many investigators in the field of capillary pressure studies have found that distilled water causes swelling and, therefore, a change in core characteristics. Also, the routine core cleaning process with any organic liquid often leaves the solid surfaces preferentially oil-wet and interstitial water determinations involving water or brine would be in error. Organic liquids such as toluene, tetrachlorethane or benzene as saturants insures the wetting of rock surfaces with a zero contact angle. From the experimental data, the irreducible fluid volume for organic liquids was greater than that for water and, therefore, a volume factor had to be applied to change irreducible liquid to irreducible water volume.

A limited search of available literature failed to reveal experimental data for adsorbed volumes with consolidated silica grains and the organic liquids used. A theoretical approach to this problem would be too involved for this paper as it would probably entail functions of free energy of wetting, the mole volumes of liquid involved, free energies of vapor adsorption on the solids, and surface tension of the liquids. In view of the lack of published data, a factor was sought that could be used to change irreducible liquid to irreducible water when the sample was clean and water-wet.

An approximate magnitude of this volume factor can be obtained from the work on liquid adsorption by unconsolidated material. It is realized that a volume factor thus determined may differ for consolidated material because of the added functions involved; however, the agreement in the experimental data indicated that either the added factors were negligible or compensating by their complexity.

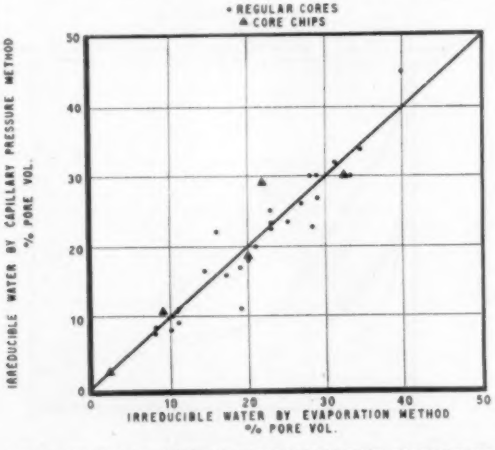


FIG. 3 — IRREDUCIBLE WATER PER CENT PORE VOLUME. EVAPORATION AND CAPILLARY PRESSURE METHODS.

Table II — Pore Fluid Retention Data

Pore Vol. 1.37 Core No. 79C

Water			Tetrachlorethane			Toluene		
Time (min)	Fluid Vol. (cc)	ΔV (cc)	Fluid Vol. (cc)	ΔV (cc)	Time (min)	Fluid Vol. (cc)	ΔV (cc)
0	1.285		1.361		0	1.300	
5	1.083	.202	1.059	.302	1	.949	.351
10	.922	.161	.790	.269	2	.704	.245
15	.762	.160	.582	.208	3	.540	.164
20	.599	.163	.452	.130	4	.450	.090
25	.458	.141	.385	.067	5	.399	.051
30	.353	.105	.346	.039	6	.365	.034
35	.305	.048	.319	.027	7	.334	.031
40	.267	.038	.298	.021	8	.314	.020
45	.240	.026	.279	.019	9	.296	.018
50	.221	.020	.264	.015	10	.279	.017
55	.202	.019	.251	.013	11	.266	.013
60	.184	.018	.238	.013	12	.252	.014
65	.167	.017	.226	.012	13	.239	.013
70	.150	.017	.214	.012	14	.227	.012
75	.134	.016	.202	.012	15	.215	.012
80	.119	.015	.191	.011	16	.204	.011

Bartell and Greager,[10] in their work with powdered silica and calcium fluoride, found the adsorbed volume to be a function of the solid surface and the degree of wetting or adhesion tension. It has been shown by Harkins and Livingston[11] and A. D. Garrison[12] that the degree of wetting of a solid by a liquid is a measure of the adhesion tension. There exists, therefore, a definite relationship between fluid adsorption and adhesion tension. Bartell and Greager used the method of Gardner and Coleman to determine the adsorption factor of various fluids with calcium fluoride and silica. They found that silica would adsorb approximately 1.13 cc of toluene or benzene to 1 cc of water. The ratio was 1.40:1 for the two liquids with calcium flouride. If a direct relationship exists between adsorption and adhesion tension, the volume factor would be 1.16:1 and 1.33:1 for tetrachlorethane on the two solid surfaces. A simplified Gardner and Coleman method was tried for limestone and dolomite and volume factors of 1.24:1 for toluene and benzene, and 1.16 for tetrachlorethane, were obtained.

Harkins and Ewing[13] found the volume of liquids adsorbed by the same charcoal increased in the same order as the percentage compression for a definite high pressure. They classified macropores as being 12×10^{-4} cm in diameter and micropores less than 10^{-6} cm. Liquid in the micropores is very highly compressed by adsorption and this compression is greater the greater the compressibility of the liquid in bulk. The relationship between compressibility in bulk and in the pores is not a direct relation since the liquid is not compressed iso-tropically. Their experiments with charcoal show an adsorption of .39 cc benzene, .35 cc water, and .41 cc of ether or a ratio of 1.11:1 and 1.17:1.

To establish a suitable volume factor that could be used in the evaporation method, a number of clean sandstone and limestone samples were selected and saturated with various fluids after the wettability of the sample to that fluid had been determined. The factor necessary to change the irreducible liquid to water volumes within the range of experimental error was found to be 1.10 for toluene and benzene and 1.13 for tetrachlorethane with limestone and dolomite.

These factors were used in all tests when liquids other than water was used.

Experimental results obtained by the evaporation method were compared with measurements on the same sample by the capillary pressure method. Since this latter method has been evaluated by previous investigators, the comparison indicates that the evaporation method is a rapid means of determining irreducible water. A total of 110 tests have been made using both methods and the general trend is shown in Fig. 3. Only the experimental results for toluene as the saturant in the evaporation method are shown since excellent agreement was obtained between the various liquids using the volume factors; each point on the curve therefore represents several tests. The method was carried out using core chips of approximately 1/10 the bulk volume of a regular core and the results are indicated in Fig. 3. The general distribution of differences between the evaporation and capillary pressure methods is shown in Fig. 4. For 54 out of 110 tests, the difference was only ±1 per cent.

In the routine determination of irreducible water saturation for core analysis, it is often advisable to study the trend of the saturation with permeability. Since permeability alone will not establish the irreducible water for a fixed type of formation such relationships have statistical significance. When a curve is determined for a particular zone of interest, it may be used to estimate the gross irreducible content of the formation and also the local values of the irreducible water saturation from the permeabilities of the individual samples. A permeability relationship for a single formation is shown in Fig. 5.

CAPILLARY PRESSURE AND PORE RADII

The role of capillary pressure has become important in the investigation of core characteristics and the values have been used by many authors[5-11] to calculate pore size distribution and permeability. In the evaporation method previously described capillary pressures and pore radii are not a part of the data but a calculation of the trend in capillary pressures can be obtained by considering the vapor diffusion as represented by Equation (1). Capillary pressure and vapor pressure lowering are a function of the liquid saturation of porous media. A qualitative relationship between these functions can be obtained by considering the water and vapor as continuous phases in the system. If at any time the two phases are in equilibrium, the equation relating the vapor pressure above a curved surface with the capillary pressure is equivalent to Equation (2) and has been reported by Freundlich,[12] Calhoun and Lewis,[2] Ledoux,[3] and others as:

$$\frac{2\delta}{r} = P_c = \frac{RT\rho_L}{M} Ln \frac{P_o}{P_v} \quad . \quad . \quad . \quad . \quad . \quad . \quad (5)$$

where ρ_L is the density of the liquid.

Since P_v is approximately equal to P_o in core samples whose capillaries are of the order of 10^{-4} cm, $Ln\ P_o/P_v$ can be written as $\frac{P_o}{P_v} - 1$ and Equation (5) can be simplified after substitution of P_v from Equation (3) to:

$$P_c = \frac{RT\rho_L}{M} \left(\frac{P_o}{QL_1/VK} - 1 \right) \quad . \quad . \quad . \quad . \quad (6)$$

Equation (6) represents a general expression for capillary pressure in terms of vapor flow from the sample during an evaporation experiment. In experimental tests, due to the air stream across the face of the core, variation in sample size and operating temperature, the values of P_o, L_1, K, ρ, are unknown but can be evaluated as constants if the capillary pressure and Q/V values are known for any saturation. The validity of the assumption that $P_c K/L$ and $T\rho_L$ remained constant or compensating after the liquid meniscus had migrated into the core can be based on the excellent agreement that was obtained between calculated and observed capillary pressure values.

The constants and capillary pressure curves were calculated for 15 samples saturated with water and the typical data are shown in Table III for Core Sample 79C. In this case, $P_c K/L$ was 14.1 x 10^{-4} gm/cm² sec and $RT\rho_L/M$ was 7.6 x 10^4 dynes/cm². Using these constants, the remaining capillary pressure values were calculated. Additional calculated and observed capillary pressure values are shown in Fig. 6 for Samples 09G and 84Z.

Examination of the calculated capillary pressure curves for the 15 samples and the necessary constants indicated that, for samples of very high permeability where the experimental capillary pressure curve was nearly horizontal to the point of irreducible saturation, two equations were necessary to represent the complete curve, one for the horizontal portion

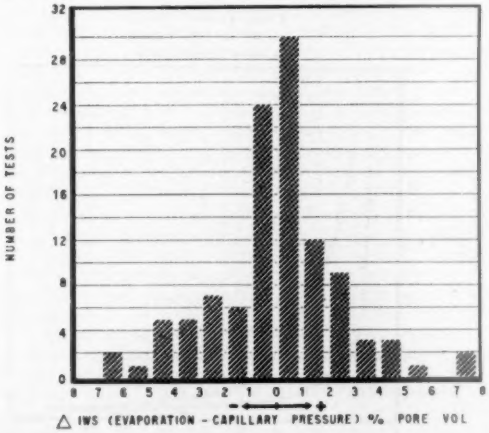


FIG. 4—DISTRIBUTION OF DIFFERENCES BETWEEN IRREDUCIBLE WATER SATURATIONS BY EVAPORATION AND CAPILLARY PRESSURE METHODS. 110 TESTS.

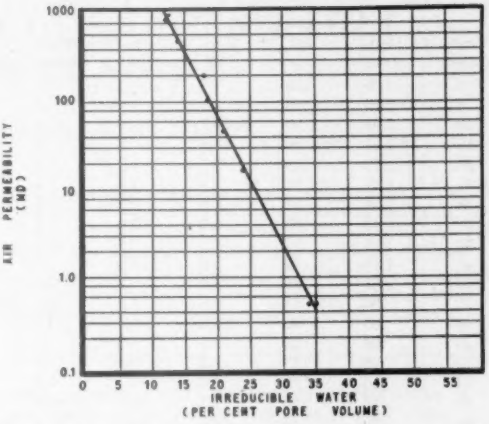


FIG. 5—IRREDUCIBLE WATER AND AIR PERMEABILITY, CAT CREEK FIELD, SECOND KOOTENAI FORMATION.

Table III — Calculated Capillary Pressure
Sample LW 20 — Water

Time (min)	Vol. (cc)[2]	Sat. %	Q/V 10^4	Cap. Pressure psi Cal.	Obser.
0	2.26	100			
5	2.18	96			.2
10	2.04	90	19.7	.1	.4
15	1.91	86	12.2	.5	.8
20	1.79	79	9.1	1.0	1.0
25	1.67	74	7.2	1.4	1.4
30	1.55	67	5.8	2.0	1.8
35	1.42	63	4.9	2.4	2.2
40	1.29	57	4.3	2.9	2.6
45	1.18	52	3.8	3.3	3.0
50	1.05	46	3.4	3.8	3.6
55	.93	41	3.0	4.3	4.0
60	.80	36	2.8	4.8	4.8
65	.68	28	2.5	5.3	5.4
70	.56	25	2.2	6.1	6.0
75	.45	20	1.9	7.1	8.0
80	.35	16	1.4	10.0	10.0
85	.29	13	1.0	14.3	17.0
90	.24	11	.8	19.4	22.0
95	.20	9	.5	29.4	26.0

and another for the vertical section. For samples whose permeability was between 100 and 600 md, one equation was sufficient to calculate the capillary pressure curve from approximately 50 per cent saturation to the irreducible value. For cores of permeability less than 100 md, one set of constants permitted the determination of a curve from 90 per cent saturation to the end point.

Because of the limited number of samples from any one formation, it was impossible to note a definite relationship between the constants and some other physical property of the core. For sandstone there was an apparent relationship between P_c, K/L and permeability; however, because of insufficient evidence, the dependency on permeability alone could not be established.

CONCLUSIONS

Investigation of the data obtained by the evaporation method, and comparison of the resultant irreducible water saturation with that obtained by capillary pressure, indicates this method fulfills the requirements for production laboratory use. Several distinct advantages of the method are:

1. The time required to determine the irreducible saturation depends on the saturant. For water, the average time was one hour.
2. Use of more volatile fluids as toluene and benzene reduces the time to approximately 20 minutes and the volume factor permits the calculation of an equivalent irreducible water saturation.
3. Since the sample tends to be oil-wet after cleaning, the solid surfaces need not be changed inasmuch as such organic liquids as toluene will wet the solid with an approximate zero contact angle.
4. The characteristics of the sample are not altered by the test and they can therefore be used for other analyses.
5. The irreducible saturation can be obtained for samples of varying size without a uniform or flat external surface.
6. The method can be used on small core chips.

If two capillary pressure values are known, the complete curve can be determined. This reduces the time element for the determination of a capillary pressure curve. Further experimental determination may indicate a relationship between the constants of Equation (6) and some other physical property such that a capillary pressure curve can be determined on the basis of the evaporation data.

ACKNOWLEDGMENTS

The author wishes to express his appreciation to the management of the Continental Oil Co. for permission to publish this paper and to J. J. Reynolds, Director, Production Research Division, for his helpful criticism and encouragement during its preparation. Acknowledgment is also made to the personnel of Continental's production laboratory for their assistance in taking data and making calculations.

REFERENCES

1. Leverett, M. C.: *Trans.* AIME (1941) **142**, 152.
2. Hassler, G. L., Brunner, E., and Deahl, T. J.: *Trans.* AIME (1944) **155**, 155.
3. Calhoun, J. C., Lewis, M., and Newman, R. C.: *Trans.* AIME (1949) **186**, 189.
4. Bruce, W. A., and Welge, H. J.: "Restored State Method for Determination of Oil in Place and Connate Water," *Oil and Gas Jour.* (July, 1947) **156**, 21.
5. Thornton, O. F. and Marshall, D. L.: *Trans.* AIME (1947) **170**.
6. McCullough, J. J., and Albaugh, F. W.: "Determination of Interstitial Water Content of Oil and Gas Sand by Laboratory Tests of Core Samples," API *Drill. and Prod. Prac.* (1944) **180**.
7. Purcell, W. R.: *Trans.* AIME (1949) **186**, 39.
8. Bikerman, J. J.: *Surface Chemistry*, Academic Press.
9. Ledoux, Edward: *Vapor Adsorption*, Chemical Publishing Co.
10. Bartell, F. E., and Greager, O. H.: "Relation of Adhesion Tension to Liquid Absorption," *Industrial and Eng. Chem.* (1929) **21**.
11. Harkins, W. D., and Livingston, H. K.: "Energy Relation of the Surface of Solids," *Jour. of Chem. Physics* (1942) **10**.
12. Garrison, A. D.: "Selective Wetting of Reservoir Rocks and Its Relation to Oil Production, API (1935) 130.
13. Harkins, W. D., and Ewing, D. T.: "High Pressure Due to Adsorption and Density and Volume Relation of Charcoal," *J. Am. Chem. Soc.* (1921) **43**, 1787.
14. Burdine, N. T., Gournay, L. S., and Riechertz, P. P.: *Trans.* AIME (1950) **189**, 195.
15. Freundlich, H.: *Colloidal and Capillary Chemistry*, Dutton and Co.

★ ★ ★

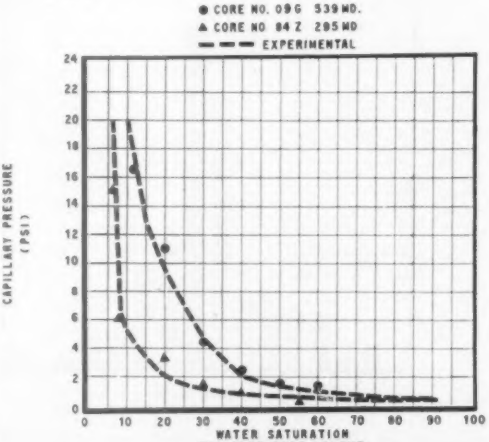


FIG. 6 — CALCULATED CAPILLARY PRESSURES.

FLUID SATURATION IN POROUS MEDIA BY X-RAY TECHNIQUE

A. D. K. LAIRD AND J. A. PUTNAM, MEMBER AIME, UNIVERSITY OF CALIFORNIA, BERKELEY, CALIF.

ABSTRACT

This paper describes the application of x-ray theory to design procedures in connection with fluid saturation determinations during fluid flow experiments with porous media. A reliable and rapid method for calibrating the x-ray apparatus is described. Extension of the method to fluid saturation determinations in three-fluid systems is described.

INTRODUCTION

In research on oil production problems a method is required which will give quickly the quantity of each component of a fluid flow system present at any cross-section of a porous medium.

The sample of porous medium under investigation is usually referred to as a core. The ratio of the volume of one component to the total fluid volume is defined as the saturation of the porous medium by that component. This ratio is generally given as per cent saturation.

Some means of measuring saturation which have received consideration include: electrical conductivity of the fluids;[1,2] emissions from radioactive tracers dissolved in the fluids; the radioactivity of silver caused by reflection of neutrons from hydrogen atoms in the fluids;[3] the attenuation of a microwave beam, the diminution and phase shift of ultrasonic wave trains,[4,5] and the reduction in intensity of x-ray beams in passing through the fluids.

X-rays have already been used with some success. Since every material has a different power to absorb x-rays, the reduction in intensity of an x-ray beam as it passes through a core depends on the fluids present. The strength of the emergent beam can be found by converting its energy into a measurable form such as heat or ionic current, or by its effect on a photographic plate or fluorescent screen. The beam strengths could be interpreted as quantities of known fluids in the core if, previously, these beam strengths had been identified with a known combination of the same fluids. With some fluid combinations it might be desirable to dissolve powerful x-ray absorbing materials in one or more of the fluids, to increase the differences in the beam strengths for various fluid saturations.

Boyer, Morgan and Muskat[6] have described a method of measuring two component fluid saturation. One component was air or water; the other, mineral seal oil in which was dissolved 25 per cent by weight of iodobenzene to increase its absorbing power. The x-ray source was a tungsten target tube operated at 43 kv potential. The beam emerging from the core was measured as ionic current flowing across an air-filled ionization chamber by means of an amplifying circuit and galvanometer. Another portion of the beam from the x-ray tube was passed through a metal plate and measured in another ionization chamber. This portion, called the monitor beam, was used as an indication of the performance of the x-ray tube. The galvanometer readings were calibrated against air-oil core saturations, gravimetrically determined. The method was apparently established by experimental means.

In the present investigation the available theory of x-radiation was surveyed with a view to extending the usefulness of the method and to developing design procedures for its application to measurement of fluid saturation in porous media. Application of the theory permits prediction of relative meter readings to be expected for any combination of porous matrix, various saturating fluids and auxiliary filtering media. It is thus possible to calibrate the equipment in terms of fluid saturation by an indirect but rapid technique. The results of calculations based on x-ray theory indicate, and results of the saturation calibration technique confirm, that a valid measurement of the saturation of the core can be made for any two components and in some cases for three components.

THEORY

The strength of an x-ray beam, after it has passed through a distance, l, of matter of density, ρ, and mass absorption coefficient, μ, at a given wavelength, λ, may be expressed by the absorption formula

$$I = I_o\, e^{-\mu\rho l} \quad \ldots\ldots\ldots\ldots \quad (1)$$

where I_o represents the intensity of the incident x-ray beam and I is the intensity of the emergent beam. The expression $e^{-\mu\rho l}$ is called the transmission factor of the material.

The variation of I_o with wavelength depends upon the materials through which the x-ray beam has previously passed and upon the spectral distribution of energy at the source of the x-radiation. A group of curves, called spectra, which show the variation of intensity with wavelength and x-ray tube voltage are given in Fig. 1. These curves represent the general radiation from a tungsten target tube. When the tube voltage is greater than 69.3 kv, the characteristic radiation of the tungsten is emitted and is superposed on the general radiation. At a given voltage the minimum wavelength λ_{min} at which energy can be emitted by an x-ray tube is given by the formula

$$\lambda_{min} = \frac{12{,}340}{\text{volts}} \quad \ldots\ldots\ldots\ldots \quad (2)$$

where λ_{min} is in Angstrom units. The wavelength at which the spectra have maximum intensity also decreases with increasing x-ray tube voltage. The area under each curve represents to an arbitrary scale the total energy emerging from the x-ray tube for that voltage.

The variation of μ with wavelength has been determined for many substances and may be found in such references as those by Compton and Allison[7] and by Hodgman.[8] The phenomenon of absorption is composed chiefly of the capture of photons by the atoms of the absorbing material with associated displacement of electrons, and of the scattering, or the deflection, of the photons by the atoms. Curves of these mass absorption coefficients show jump discontinuities, or absorption edges, at wavelengths which are short enough for the photons,

[1] References given at end of paper.

Manuscript received in the office of the Petroleum Branch Oct. 30, 1950. Paper presented at the Fall Meeting of the Petroleum Branch in Los Angeles, Calif., Oct. 26-21, 1949.

or bundles of x-ray energy, to be at a high enough energy level to eject electrons from the successive shells of the atoms (c.f. pp 526-531 of Compton and Allison).[7] These edges are given the designations *K*, *L*, *M*, etc., of the corresponding atomic electron shells from which the electrons are ejected. This added means of capturing photons causes the material to be a much more effective absorber on the shorter wavelength side of each discontinuity. The absorption edges of the elements occur at decreasing wavelengths as the atomic numbers increase.

The curves of ionization chamber efficiency as a function of wavelength shown in Fig. 2 were calculated by means of the approximate theory given on pp 484-496 of Compton and Allison.[7] The chamber gases with the higher product $\mu\rho$ produce the higher ionization chamber efficiencies, except possibly on the shorter wavelength side of an absorption edge. In calculating these curves, the effect of scattering on the chamber efficiency has been neglected without impairing their usefulness.

When x-radiation is absorbed in a gas, ions are produced in proportion to the energy of the x-ray beam. In the ionization chamber, the electrical potential between the collecting plates should be kept high enough to sweep practically all the ions formed to the plates. If the ionic current so produced is strong enough it may be measured and thus indicate the strength of the x-ray beam entering the ionization chamber.

Since each fluid has a different absorption characteristic, it should be possible to determine an unknown core fluid saturation from the ionization current meter readings, by referring to a previous calibration in which the meter readings had been identified with known core saturations with the same fluid.

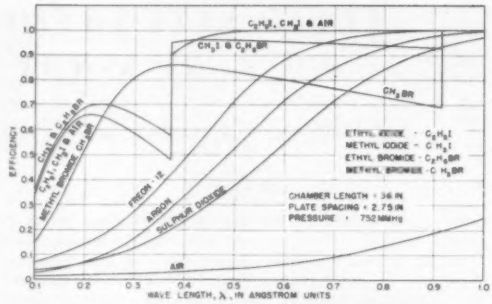


FIG. 2 — IONIZATION CHAMBER EFFICIENCY FOR DIFFERENT GASES.

The relative meter readings to be expected from combinations of core saturations by different fluids may be calculated in the following manner. The spectral intensity at each wavelength for a given x-ray tube voltage may be multiplied by the ionization chamber efficiency and by the fraction of the beam transmitted by each material in its path. The values so calculated may then be plotted as a function of wavelength. The area under the resulting curve represents the meter reading to an arbitrary scale. These operations are illustrated in Fig. 3.

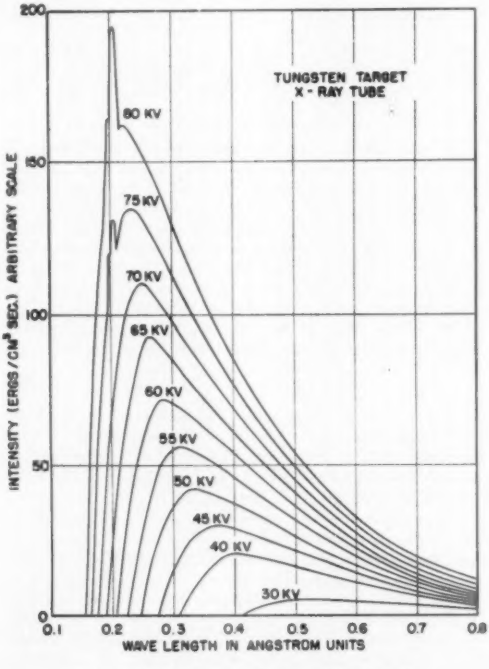


FIG. 1 — X-RAY SPECTRA AT DIFFERENT VOLTAGES.

APPARATUS

X-Ray Equipment

The source of x-radiation was a thermax, 140 KVP, water-cooled, tungsten target tube, manufactured by Machlett Laboratories. The continuous rating of the tube was 11 milliamperes at 100 kv peak. The tube was mounted in a shockproof, rayproof head, connected by eight feet of shielded cable to a Westinghouse, 100 KVC, industrial type, x-ray transformer and control panel.

A General Electric automatic voltage stabilizer, rated at 2 KVA on 230 v service, was used to reduce fluctuations in the x-ray power supply voltage. A Type 1226, 2.4 KVA Powerstat, variable voltage transformer in parallel with the x-ray control panel, supplied a non-reactive load and was adjusted manually to keep a constant load on the stabilizer. This arrangement was used to avoid the change of effective x-ray tube voltage at a given peak voltage, caused by the variation of stabilizer output wave form with load.

The x-ray tube current was indicated by a milliammeter with a 0.2 ma least count. The high potential transformer primary voltage and the x-ray tube potential were indicated by a voltmeter with a least count of 1 v on its 0-150 v scale, and of 2 v on the 0-300 v scale. The relation between the readings of this meter and the x-ray tube peak voltage was established by means of a standard sphere-gap. The voltage output of the stabilizer was indicated by a push-button meter on the control panel. Ammeters were provided for the stabilizer output and the high potential transformer currents.

Changes in temperature of the high potential transformer of as little as 2°F caused noticeable differences in electrometer readings. Consequently, a small heat exchanger was installed to transfer heat from the transformer oil to cooling water. Circulation was effected by means of a small reciprocating

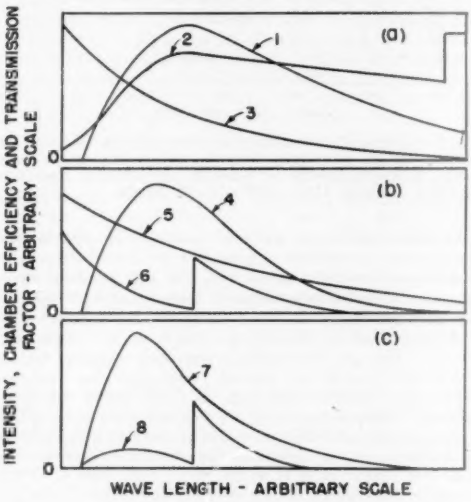
pump. This arrangement held the transformer temperature within satisfactory limits.

Ionization Chambers and Electrometers

A 110 v Sola, constant voltage transformer was used on the supply to the electrometer rectifier circuit. This common rectifying circuit supplied two direct current amplifiers, each connected to an electrometer circuit mounted on an ionization chamber. The circuits used were of the same type as those described by G. L. Mellen.[9] These electrometers could be attached to either ionization chamber and to either amplifying circuit. All exposed electrical wiring was shielded. The reading of the electrometer attached to the monitor ionization chamber was recorded with each reading of the core ionization chamber electrometer, so that no momentary fluctuation in x-ray output would go undetected during a set of readings.

Both ionization chambers were made of 5 in. diameter, ⅛ in. thick brass tubing. The core chamber was 36 in. long, and the monitor 24 in. long. The parallel brass collecting plates, 2¾ in. wide and 1/16 in. thick were symmetrically placed 2¾ in. apart with at least ⅛ in. air gap all around. Polysterene was used to support and insulate the plates from the grounded shell. "Kovar" seals were used to insulate the plate connections from the shell. The entrance and exit windows of the chambers were of AM 3-SH, magnesium alloy, 1/32 and 3/32 in. thick, respectively. A capped tube was sealed into each shell and through the lead shielding to simplify filling the chambers.

The ionization chamber plate potential of approximately 900 v was taken from a group of 150 v dry cell batteries.



CURVE 1 SPECTRAL CURVE AT A GIVEN X-RAY TUBE POTENTIAL.
2 IONIZATION CHAMBER EFFICIENCY
3 TRANSMISSION FACTOR FOR THE SOLIDS AND AIR IN THE X-RAY BEAM PATH.
4 PRODUCT OF ORDINATES OF CURVES 1, 2 & 3.
5 TRANSMISSION FACTOR FOR THE FLUID IN THE CORE.
6 SAME AS 5 BUT FLUID HAS AN ABSORPTION EDGE.
7 PRODUCT OF THE ORDINATES OF CURVES 4 & 5.
8 SAME AS 7 FOR CURVES 4 & 6.

THE RATIO OF THE AREAS UNDER CURVES 7 & 8 GIVES THE RATIO OF THE METER READINGS TO BE EXPECTED.

FIG. 3 — DIAGRAM SHOWING A TYPICAL EXAMPLE OF CALCULATIONS TO PREDICT RELATIVE METER READINGS.

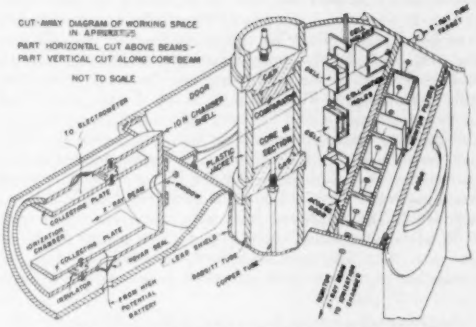


FIG. 4 — CUT-AWAY VIEW OF X-RAY APPARATUS.

Porous Media

The porous media tested were Norton cylindrical consolidated alundum cores, 1 in. in diameter and 5 in. long. They had a porosity of about 26 per cent.

A 1 in. diameter piece of Alcoa 24 ST aluminum alloy about ½ in. long was cut on two parallel chords to a thickness of about 0.8 in. This piece, called the comparator, was placed on one end surface of the core. With each set of core electrometer readings a reading was taken with the x-ray beam passing through the flattened part of the comparator to show that the x-ray producing and indicating circuits were performing satisfactorily. The comparator also gave a datum for resetting circuit constants when desired. The comparator need not be mounted integrally with the core but it should be so located that it can be scanned by the x-ray beam independently of the core.

A brass cap with threaded tubing connections was provided for each end. The cap next to the aluminum had two holes communicating with the core through the aluminum. The cap at the other end had one hole to the core. The annular space around the core and aluminum, between the two caps, was filled with thermosetting plastic, Paraplex P-43. This jacket was machined to approximately 1.5 in. diameter.

General Arrangement

The x-ray head, ionization chambers and the working space between them were enclosed in lead. Tubing connections were made to the core caps through 2 in. diameter babbit tubes running in packing glands on the lead shield of the working space. The core was held at a constant elevation by the babbit tubes. The fluid piping and the babbit tubes were attached to a frame which permitted the core to be rotated about its axis through an angle of 76°. Fig. 4 illustrates the arrangement.

EXPERIMENTAL TECHNIQUES

X-rays are affected by the elements through which they pass, without regard to their chemical or physical arrangement. Advantage was taken of this fact to develop a method of identifying the electrometer readings with fluid saturation. The fluids were put in a box, or cell, shown in Fig. 4, which

presented a fluid path length to the incident x-ray beam equal to that in the core. A number of these cells was mounted on a rack-and-pinion which permitted insertion of the cells into the x-ray beam. By this arrangement, the amount of the materials in the path of the x-rays remained the same; merely the order was changed. The length of the fluid path in the core was approximately equal to the product of the core diameter and porosity. The effective path is slightly less than the diameter because of the core curvature, but approaches the core diameter as the x-ray beam diameter decreases. The core and beam diameters were known and the effective path length was calculated. The thin-sided cells were made up of Paraplex P-43, of breadth inside equal to the effective path length of the core. Partitians were built into some cells to allow the simulation of various fluid saturation combinations in increments of 25 per cent.

To prepare a core for fluid calibration, its dimensions were taken and it was then encased in plastic and mounted in the apparatus as previously described. The core was scanned with the x-ray beam on three diameters, spaced 38° apart, over the full length, to test for uniformity of porosity. The calibration required was then carried out at several voltages close to the one chosen for the particular system of materials.

During a calibration, each well was positioned in the x-ray beam by reference marks attached to the rack. In this way, readings could be taken corresponding to several percentages of fluid saturation without opening the door of the core compartment.

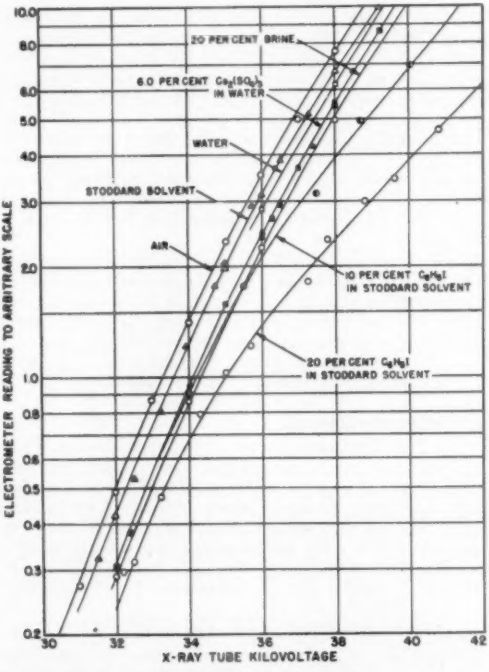

ELECTROMETER READING TO ARBITRARY SCALE
X-RAY TUBE KILOVOLTAGE
20 PER CENT BRINE
6.0 PER CENT $Ce_2(SO_4)_3$ IN WATER
WATER
STODDARD SOLVENT
AIR
10 PER CENT C_6H_5I IN STODDARD SOLVENT
20 PER CENT C_6H_5I IN STODDARD SOLVENT

FIG. 5 — EXPERIMENTALLY DETERMINED ELECTROMETER READINGS AS A FUNCTION OF X-RAY TUBE POTENTIAL USING CELLS FILLED WITH FLUIDS INDICATED, PLACED IN FRONT OF AN AIR FILLED ONE-IN. DIAMETER ALUNDUM CORE. LOW VOLTAGE RANGE.

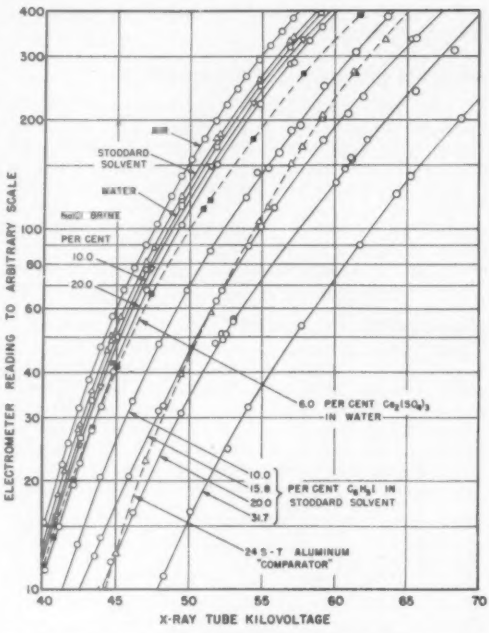


FIG. 6 — EXPERIMENTALLY DETERMINED ELECTROMETER READINGS AS A FUNCTION OF X-RAY TUBE POTENTIAL USING CELLS FILLED WITH FLUIDS INDICATED, PLACED IN FRONT OF AN AIR-FILLED ONE-INCH DIAMETER ALUNDUM CORE, HIGH VOLTAGE RANGE.

In calibrating a core and fluid system to be used in flow experiments, to be sure of getting a good calibration, one should make up cells in sets based on cell breadths corresponding to several percentages of porosity on both sides of the given percentage. In this investigation, it was sufficient to make up one set of cells corresponding to the known per cent porosity, and four other cells representing complete saturation by one fluid for two porosity percentages above and two below. After the core had been filled with liquid, the meter reading, corresponding to 100 per cent saturation of the filling fluid, was compared with the readings obtained with the cells of assorted sizes, to determine the effective porosity of the core.

Systems of Fluids and Filters

The fluids used in the saturation calibration tests were air, boiled tap water, aqueous solutions of sodium chloride and cerium sulphate, a mixture of light hydrocarbons known as Stoddard solvent, and mixtures of Stoddard solvent and iodobenezene.

Filters of barium dioxide, of various thicknesses, as indicated by the theory, were made up by tamping powdered barium dioxide into Paraplex cells. These filters, inserted between the x-ray tube and the core, were used to change the relative magnitude of the meter readings. Although the use of filters with monochromatic radiation may be advantageous, no improvement in the present system was obtained.

The above fluids were combined into systems that might coexist in a core as two or three components. The effect of

Table I — Meter Readings as a Function of Voltage and Core Porosity

Voltage	Per cent Porosity					
kv	21	23	25	Filled Core	27	29
59	172.5	167.5	164.5	163.0	163.0	161.5
60	185.0	182.5	179.0	178.8	179.0	177.0
61	198.0	195.5	192.0	191.0	190.0	188.0

Average porosity = 26.0 ± 0.5 per cent

these systems was determined by performing a calibration test on each, over the range of voltages from 30 to 90 kv, both with the barium dioxide filter and without it.

An interesting use of the comparator was in the magnification of the difference between meter readings for two different fluids. For example, water and Stoddard solvent gave comparatively small differences of meter readings during fluid saturation calibration, as indicated by Figs. 5 and 6. With ordinary use of the electrometer, this difference was too small to give satisfactory precision, because of the errors in reading the meter. This small difference was magnified by manipulating the electrometer. The meter was operated at low sensitivity at a voltage such that the comparator and the smaller of the two fluid readings coincided. This is always possible at a voltage high enough for readings to be made on a low sensitivity scale by using a thinner comparator and adding extra metal in the beam path externally as required. The x-ray tube was left operating and the electrometer zero adjuster was turned to zero the meter with the x-ray beam passing through the comparator. The meter was then switched to a higher sensitivity scale and the two fluid readings were taken. Proper choice of sensitivity gave nearly full scale differences in readings, with corresponding increase in the precision of the fluid saturation determinations. Upon completion of the reading, the meter was switched back to the low sensitivity scale and the zero adjustment was turned to give the original comparator reading. The return of the meter to its customary zero upon shutting off the x-ray tube circuit was considered as evidence that the settings had been made accurately.

RESULTS

The experimentally determined electrometer readings as a function of x-ray tube potential, using cells filled with the various fluids mentioned above and placed in front of an air-filled alundum core, are shown in Figs. 5 and 6. The curves drawn on these figures were faired in so as to best represent the experimental data. A table of the coordinates of these curves is available.[9] Similar data and curves are available in the tube potential range 70 kv to 90 kv but are not included here as still another logarithmic cycle would be required and the experimental points all fell on the monotonic curves representing the data. It is to be noted that the greatest scatter of the data occurs in the tube potenial range below 40 kv. In this region the experimental error is not better than five per cent. In the neighborhood of 40 kv the error is about two per cent and decreases to considerably less than one per cent at the higher voltages.

The dashed curves shown in Fig. 7 were obtained by taking direct ratios of the electrometer readings for any given fluid to the readings for air at corresponding tube potentials and utilizing the faired curves shown in Figs. 5 and 6. The solid curves of Fig. 7 represent the corresponding ratios calculated from theory. The reasonably close agreement between the two sets of curves demonstrates that the method of predicting meter readings is satisfactory.

Some data taken during tests of the validity of the cell method of establishing a core saturation calibration are shown in Table I. The meter readings were taken at three neighboring x-ray tube voltages with five cells representing 100 per cent liquid saturation of cores with porosities ranging from 21 to 29 per cent. The core was then filled and readings were taken at the same voltages. Analysis of the data shows that the reading at 60 kv for the 27 per cent porosity cell was in error. The average porosity indicated was 26 per cent, which is the value found for similar cores by other methods. Any discrepancies that might have appeared in this check could have been due to incomplete filling of the core, to faulty porosity data for the core or to the inaccuracy of the cell calibration data or method.

The approximate core porosity and its variation on different diameters are shown in Table II for two cores. In this method, variations of porosity resulted in approximately twice the percentage variation in meter readings.

DISCUSSION

The spectra shown in Fig. 1 were developed from average values of published spectra for tungsten target x-ray tubes. The wavelengths of the maximum intensities of the curves shown were determined by experiments designed to establish

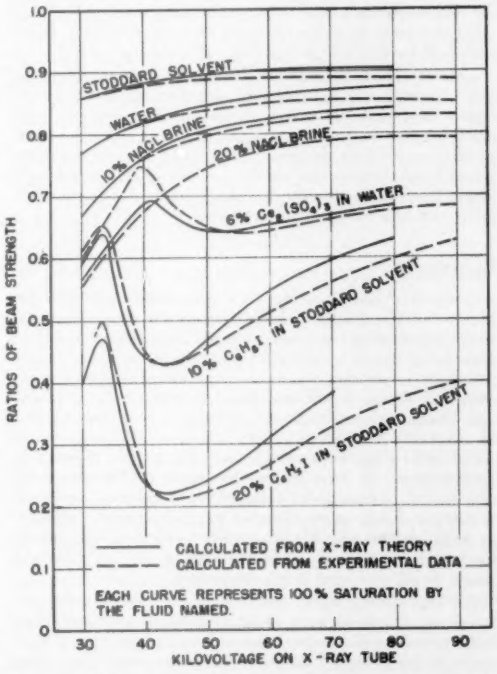

RATIOS OF BEAM STRENGTH
KILOVOLTAGE ON X-RAY TUBE
STODDARD SOLVENT
WATER
10% NACL BRINE
20% NACL BRINE
6% Ce2 (SO4)3 IN WATER
10% C6H5I IN STODDARD SOLVENT
20% C6H5I IN STODDARD SOLVENT
CALCULATED FROM X-RAY THEORY
CALCULATED FROM EXPERIMENTAL DATA
EACH CURVE REPRESENTS 100% SATURATION BY THE FLUID NAMED.

FIG. 7 — RATIOS OF STRENGTHS OF X-RAY BEAMS EMERGING FROM CORE CONTAINING DIFFERENT FLUIDS AT VARIOUS VOLTAGES, TO THOSE FROM CORE CONTAINING AIR. NO FILTER.

Table II — Uniformity of Core Porosity

Distance from end of core in in.	Per cent Porosity of Core				
	Core 1		Core 2		
	Diam. 1	Diam. 3	Diam. 1	Diam. 2	Diam. 3
1/8	26.6	26.0	—	—	—
3/8	25.7	25.4	26.0	26.0	26.4
5/8	26.0	27.4	26.0	26.0	26.4
7/8	25.7	26.0	26.2	26.0	26.4
1 1/8	25.7	26.0	26.4	26.7	26.7
1 3/8	25.4	26.0	26.6	26.8	26.6
1 5/8	26.0	26.0	26.6	26.7	26.5
1 7/8	26.0	26.3	26.6	26.5	26.3
2 1/8	26.0	26.0	26.7	26.7	26.4
2 3/8	26.0	26.0	26.5	26.8	26.9
2 5/8	26.0	26.0	26.7	27.4	27.4
2 7/8	26.0	26.0	27.2	27.5	27.6
3 1/8	26.0	26.0	27.2	27.5	27.6
3 3/8	26.1	26.0	27.1	27.4	27.3
3 5/8	25.9	26.0	27.2	27.5	27.0
3 7/8	25.9	26.0	27.1	27.4	27.3
4 1/8	25.9	26.0	27.4	27.4	27.4
4 3/8	25.7	26.0	27.3	27.4	27.4
4 5/8	26.0	26.0	27.8	28.0	28.0
4 7/8	26.0	26.0	27.8	27.7	27.6

Diameters 1 and 3 were 76° apart and Diameter 2 was 38° from both.

the relation between tube voltages and the effect of the absorption edges upon the meter readings. These spectra make useful analytical predictions of experimental results possible.

General x-radiation was used in this exploratory investigation because it was believed that with it results could be obtained more certainly and economically than with the very much weaker narrow wavelength band, or monochromatic x-radiation. A small amount of work done with selected wavelength bands gave results similar to those using general radiation. There may, however, be some cases where monochromatic radiation would be advantageous.

Equipment

Commercial equipment was used as the source of x-radiation because of its simplicity and relatively low cost. Similarly, ionization chambers and direct current amplifiers provided an economical means of indicating the strength of x-ray beams. Atmospheric pressure was used in the ionization chambers to avoid any change of efficiency characteristics due to gas leakage. Under this condition methyl bromide was used because of the resultant high ionization chamber efficiency. In the wavelength range between 0.3 and 0.6. A, the efficiency is approximately 80 times greater than with air. This compound also has the advantage of being a vapor at room conditions so that the density in the chamber was independent of changes in room temperature. If the chamber were kept at constant temperature, mixtures of some other compounds might be used which would give even better efficiencies.

For high absorption of x-rays from the primary beam the ionization chambers were made as long as practical. Similarly, to reduce the losses to the shell and plates from fluorescence of the gas, the chambers were made wide. The dimensions were limited by space, cost and the potential necessary between the collecting plates to ensure a high yield of current from the ions produced. To prevent the build up of static charges under x-ray bombardment, all parts of the chambers except the insulators were made of metal.

Choice of Fluids

The fluids used in the saturation calibration were selected for their chemical stability and mutual insolubility. The powerful absorbers used to accentuate the effect of one component had to be soluble in that component alone. Cerium sulphate and cerium chloride made it possible to use the absorber in water. Cerium was the only heavy element found which had compounds suitable for use in aqueous solution, that is, they would not decompose nor precipitate. Sodium chloride brine was satisfactory, and also represented common saline solutions occurring in many oil fields. Stoddard solvent was a satisfactory liquid hydrocarbon component, but many other oils might have been used as well or better. Iodobenzene was used in the oil and appeared to be satisfactory for tests of a month's duration.

Tests were made on the decomposition of cerium sulphate and iodobenzene under the influence of x-radiation. Tests were continued for four hours continuous irradiation without any change being noted. The sensitivity of the measurement was about one per cent.

A comparison of the absorption power of solutions of cerium sulphate in water and of iodobenzene in oil was made on old and new samples of these materials. After three months standing, the cerium sulphate solution had not changed. The iodobenzene solution, however, had decreased approximately six

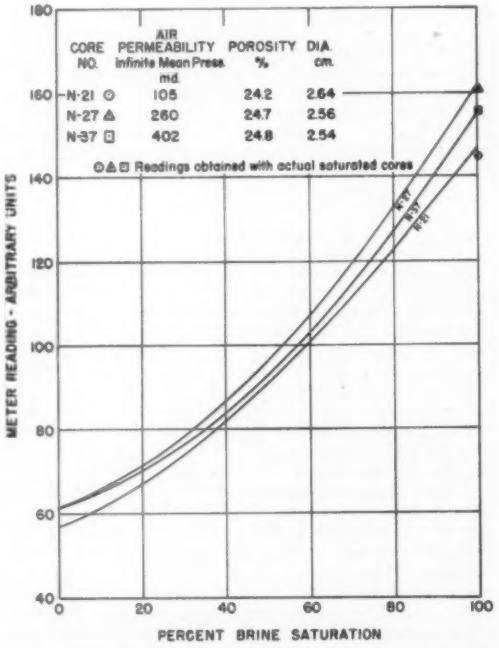


FIG. 8 — CALIBRATION CURVES ESTABLISHED BY CELL METHOD FOR THREE ALUNDUM CORES AND FLUID SYSTEM OF BRINE (0.5N NaCl IN DISTILLED WATER) AND OIL (20 WT. % C_6H_5I IN ISO-OCTANE).

per cent in absorbing power, although it had been shielded from light and tightly stoppered.

Small samples of Paraplex were tested for absorption of fluids and consequent effect on x-ray measurements. Samples were soaked in air, water, a six per cent cerium sulphate solution, and a 16 per cent mixture of iodobenzene with Stoddard solvent. Frequent tests made over a period of four weeks showed no detectable changes.

Two-Component Saturation Measurement

In Fig. 8 are shown calibration curves for three different alundum cores. These curves were established by use of the cell technique for 61 kv x-ray tube voltage. At the time of writing this report cores of known two-fluid saturation had not yet been compared with the calibration curves except at 100 per cent brine saturation as shown in Fig. 8. At least at this saturation the deviation of the plotted points is within the accuracy of the method.

Maximum accuracy of the present apparatus may be estimated as follows: by using an absorber in one component, the electrometer could be made to show a difference in direct reading of 150 units between 100 per cent saturation by one component and 100 per cent saturation by the other component. When the meter was used this way the reproducibility of a single reading was within two units, and for many readings the mean was probably within one-half unit of the calibrated value. This indicates an error of less than 0.5 per cent. If by means of the comparator the magnification of the meter reading differences were carried out carefully, an error of less than one per cent might be expected without any absorbers having been added to the fluids. Other errors due to changes of the fluid properties and of the equipment characteristics might increase the error by a small amount. The use of the comparator, however, assures that the total errors will be of the same size as the errors in setting the electrometer circuit constants, which are less than one per cent. Consequently, it is reasonable to suppose that the total error in fluid saturation measurement would be less than twice the estimated error, that is, less than two per cent.

Three-Component Saturation Measurement

According to the theory it should be possible to extend the x-ray technique to saturation determinations for three-fluid components. In order to determine the saturation of n components, n-1 readings, each at a different voltage, would be necessary. The *nth* component can then be found by difference. Further, the rate of change of readings with saturation would have to be different for the various voltages employed. This requirement is equivalent to the conditions of the linear independence of n simultaneous equations.

The following describes a calculated calibration for a three-component system utilizing air, a brine composed of 20 weight per cent sodium chloride and a light hydrocarbon oil known as Stoddard's Solution.

Since Equation (1) applies to a single wavelength it was put in the following form:

$$\frac{I}{I_g} = \frac{\int_{\lambda_{min}}^{\infty} (I\eta' F') e^{-l\left[(S\rho\mu')_o + (S\rho\mu')_w + (S\rho\mu')_g\right]} d\lambda}{\int_{\lambda_{min}}^{\infty} (I\eta' F') e^{-l\,(S\rho\mu')_g} d\lambda} \quad (3)$$

where I is proportional to the meter reading with three fluids in the core.

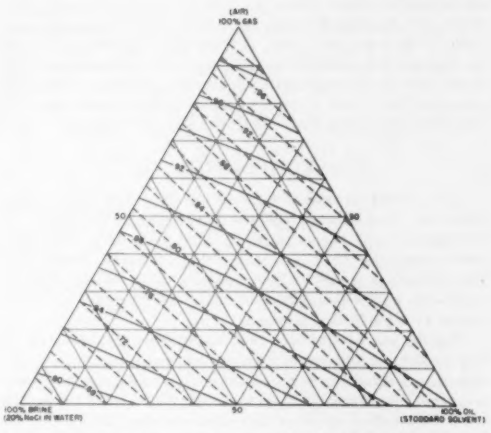


FIG. 9 — CALCULATED LINES OF CONSTANT METER READING REFERRED TO METER READING WITH AIR-FILLED CORE. SOLID LINES AT 70 KV AND DASHED LINES AT 34 KV.

I_g is proportional to the meter reading with only air in the core.

I', η', F' represent target radiation intensity, ionization chamber efficiency and transmission factor for the solids and air in the x-ray beam path. Evaluation of these factors is described by Laird.[10]

l = effective path length of x-rays through the fluid in the core and is approximately equal to the product of the core diameter and porosity.

S = saturation of fluid in the core.

ρ = fluid density.

μ' = mass absorption coefficient of the fluid.

Subscripts (o), (w) and (g) refer to oil, brine, and air respectively.

All terms with superscript (′) are dependent upon the wavelength.

In equation (3) the term $e^{-l\,(S\rho\mu')_g}$ equals unity because the product $\rho\mu'$ is negligible compared to the corresponding values for the liquids.

Equation (3) was then evaluated by means of a rather lengthy tabular calculation procedure and graphical integration of curves similar to curve 7 of Fig. 3 in order to cover the appropriate wavelength ranges corresponding to 70 kv and 34 kv. The results are plotted in Fig. 9, which shows the fluid saturations in conventional manner on a triangular coordinate scheme. The solid lines represent constant values of the ratio of meter reading with three fluids present to meter readings with only air in the core at 70 kv. The dashed lines represent the same ratio of readings for 34 kv.

In application, suppose that a core has these three fluids present but in unknown amounts and that at 70 kv and at 34 kv reading ratios of 0.88 and 0.82, respectively, are obtained. The point of intersection of these two curves on Fig. 7 shows that the core contains, at the point of measurement, 30 per cent brine, 40 per cent oil, and 30 per cent air.

Although the calibration procedure described here for three components has not yet been verified by direct comparison with a core of known three-phase saturation, the procedure is theoretically possible. However, assuming that the electrometer reading ratios can be obtained to an accuracy of 0.5 per cent

the three-fluid saturations, according to Fig. 9, could have maximum theoretical errors as follows: oil, ±10 per cent; gas, ±5 per cent, and brine, ±4 per cent. These errors could be considerably reduced by utilizing fluid combinations that would give larger intercept angles on Fig. 9. In any event, the practical use of the three-component method leaves much to be desired and it certainly requires further development.

CONCLUSION

The present investigation indicates that the approximate theory of x-radiation may be used satisfactorily to predict the strength of x-ray beams emerging from cores of porous materials containing various combinations of fluids. The theory thus permits a survey to be made of a wide variety of materials with a view to selecting suitable combinations for application to a particular problem.

Making use of the fact that absorption of x-radiation is independent of the order in which various materials are traversed, a method has been developed for calibrating the x-ray emergent beam strengths in terms of fluid saturation of the core. This method employs equivalent absorbing media thereby avoiding the difficulties associated with changing the saturation of a core which would be employed in a direct calibration procedure.

A method for determining the saturations in a three-fluid system has been shown to be theoretically feasible, but requires additional development to place it on a practical basis.

ACKNOWLEDGMENTS

This investigation was carried out as a part of the activities of Research Project 47A of the American Petroleum Institute. The cooperation and financial support of that organization is gratefully acknowledged. Special thanks are due to R. W. Ravenscroft, A. E. Peck, F. E. Snodgrass and R. E. Buckland for assistance with the experiments. For assistance in the design of the ionization chambers, special thanks are due to B. J. Moyer of the Radiation Laboratory.

REFERENCES

1. Leverett, M. C.: *Trans.* AIME (1939) **132**, 149.
2. Wyckoff, R. D., and Botset, H. G.: *Physics* (1936), **7**, 325.
3. Brunner, E., and Mardock, E. S.: *Trans.* AIME (1946) **165**, 133.
4. Keller, E. G.: Tech. Report No. 2, API Project 47A (Oct., 1948).
5. Keller, E. G., Smith, O. J. M., and Putnam, J. A.: Tech. Report No. 3, API Project 47A (July, 1949).
6. Boyer, R. L., Morgan, F., and Muskat, M.: *Trans.* AIME (1947) **170**, 15.
7. Compton, A. H., and Allison, S. K.: *X-Rays in Theory and Experiment, 2nd Ed.*, D. Van Nostrand, New York (1935).
8. Hodgman, C. D.: *Handbook of Chemistry and Physics, 30th Ed.*, Chemical Rubber Pub. Co., Cleveland (1947).
9. Mellen, G. L.: *Electronics* (April, 1946) **19**, 1-6, 142.
10. Laird, A. D. K.: MS Thesis, University of California (1949).

DISCUSSION

By W. J. West, California Research Corp., La Habra, Calif.

The authors have essentially followed the method of Boyer, Morgan, and Muskat in measuring fluid saturations of cores. It might be worthwhile to point out the similarities and the distinguishing features of the two methods. The authors of the present paper have used a strong absorber in the oil component as was done earlier by Boyer, Morgan and Muskat. The experimental apparatus and method of calibration are essentially the same. The difference is that Laird and Putnam have analyzed the theory of absorption of the entire spectrum of an x-ray tube and have shown that there are optimum voltages across the x-ray tube that will give maximum accuracy. These optimum voltages are shown to be related to the critical absorption wavelength of the absorbing element.

The theory was extended to show the possibility of using three fluid components, but no experimental work was done to confirm the theory. The authors have shown that the accuracy to be expected for a three-component system is rather poor. This inaccuracy is largely a result of the small angle of intersection of the dashed and solid curves of Fig. 9. The requirement of the use of two liquids that give slopes of meter readings *vs* saturation of opposite sign, plus the requirement that the angle of intersection be large as possible, greatly limits the fluids that could be used in the proposed method of measuring saturation in a three-component system.

The experimental apparatus appears quite satisfactory. A good job seems to have been done in stabilizing the output of the x-ray tube. The troubles involved with ion chambers due to their bulkiness, their high background readings, and zero drift are conveniently and simply eliminated by the use of Geiger counters.

The question arises as to what is to be done for core materials that are non-uniform in porosity or chemical composition, or both. Apparently a fluid calibration using the liquid cells must be made for each point along the sample and means provided whereby the core sample is returned to those exact positions during the test run.

The x-ray absorption edges of the elements can be used in a somewhat different manner for determining the amount of a given element that is present in the core. They have been so used by Arne Engstrom[1] to analyze biological materials. His method is essentially independent of core materials and other liquids present.

The method is described briefly as follows: Referring to Fig. 1-A, let the wavelength λ_c be the critical absorption wavelength of one of the elements in the test sample. Let the wavelength of a monochromatic beam of x-rays be changed from λ_1 to λ_2, λ_1 and λ_2 being on opposite sides of the critical absorption wavelength at which the transmitted intensity changes

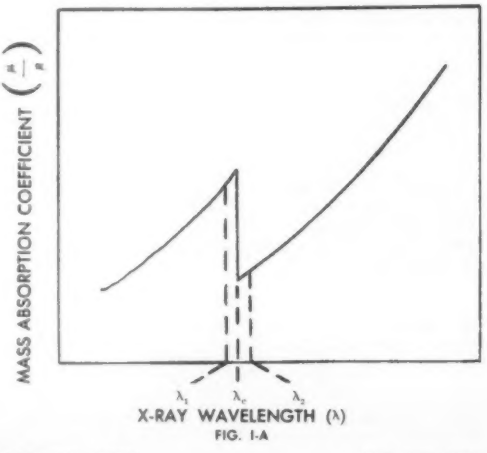


FIG. 1-A

abruptly. When λ_1 and λ_2 are close to λ_e, the ratio of the intensities at λ_1 to those at λ_2 is

$$\frac{I'_1/I_1}{I'_2/I_2} = e^{-\left[\frac{\mu_1}{\rho} - \frac{\mu_2}{\rho}\right]\rho x} \quad . \quad . \quad . \quad . \quad . \quad (1)$$

provided no other elements in the path of the x-ray beam have absorption edges in the wavelength range λ_1 to λ_2. I'_1 and I'_2 are the transmitted, and I_1 and I_2 are the incident intensities of the x-ray beam at wavelengths λ_1 and λ_2. The change in the mass absorption coefficient $\left[\frac{\mu_1}{\rho} - \frac{\mu_2}{\rho}\right]$ at the absorption edge is known for nearly all the elements. The mass in grams of core material per square centimeter of the x-ray beam is just ρx and can be calculated from Equation (1).

This method is somewhat more elaborate than the usual absorption type method because it utilizes monochromatic radiation. A curved crystal type monochrometer could be used or a system of Ross balanced filters. The Ross filters would be simpler and more economical, but would restrict the number of elements that could be used for indicators.

The Engstrom method would be unaffected by non-uniformity in porosity and independent of the chemical composition of the core, provided that the elements used for indicators were not present in the core material.

REFERENCE

1. Engstrom, Arne: *Quantitative Micro- and Histochemical Elementary Analysis by Roentgen Absorption Spectrography, Acta Radiologica Supplementum LXIII*, P. A. Mosstedt and Soner, Stockholm (1946).

DISCUSSION

By Alexander Grenall, Union Oil Co. of California, Wilmington, Calif.

At the time that Boyer, Morgan and Muskat[1] presented their paper describing application of the x-ray absorption technique to studies of core saturation, there was considerable discussion of the method. Among those offering criticisms was Frevel, a well-known investigator in the field of x-ray techniques, who pointed out that the accuracy and sensitivity of the method suffered materially from the use of white x-rays, and that the selection of an ionization chamber as x-ray detector in preference to a sensitive Geiger-Muller counter was not explained in the text.

The present work is subject to the same analysis. There are a number of points which I am interested in commenting on but perhaps the discussion regarding use of white x-rays could bear amplification from the point of view of x-ray theory.

It is known that the quality of a white x-ray beam changes with the type and thickness of material penetrated. Fig. 1-B illustrates the effect of thickness.[2] The first layers of the absorbing material remove a large fraction of the "soft" radiation and only the "hard" portions reach the final layers. Thus the mass absorption coefficient, μ/ρ, is effectively greater in value for rays entering an absorber than for those that leave.

The fundamental absorption equation,

$$I = I_o e^{-\mu/\rho\, \rho\, l} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

is derived on the assumption that μ/ρ is constant over all values of the path length, l. This has been shown experimentally to hold only for monochromatic radiation. Thus Equation (1) cannot be applied directly to the case of white x-rays.

If we force the use of Equation (1) it becomes necessary

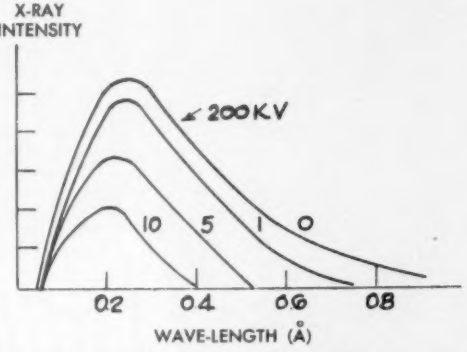


FIG. 1-B — CURVES SHOWING THE EFFECT PRODUCED ON X-RAY INTENSITY AND WAVE-LENGTH WHEN A HETEROGENEOUS X-RAY BEAM IS PASSED THROUGH 1, 5 AND 10 MM OF ALUMINUM.

to account for the variation of μ/ρ with wavelength. This may be attempted as follows. It has been shown empirically[3] that, for certain wavelength ranges the relationship is,

$$\mu/\rho = \frac{1.60 \times 10^{-2}\ \Sigma^{3.94}\ \lambda^3}{A} + \frac{\sigma}{\rho} \quad . \quad . \quad . \quad (2)$$

where Σ = atomic number, λ = wavelength, A = atomic weight and σ/ρ = scattering coefficient, given as 0.2 for $\Sigma > 6$ and 0.15 for $\Sigma < 6$. The use of Equation (2) is open to the objection, however, that it does not hold adequately when it becomes necessary to express absorptions over a wide range of wavelengths and materials, as in the present case. A more complex relationship must be developed.

Further complications are added when various kilovoltages are employed in generating white x-rays. Different wavelength ranges are produced with different intensity distributions in each case. It then becomes necessary to evaluate each kilovoltage setting in terms of the expressions discussed previously.

Still another uncertainty in measurement is introduced when fluctuation of voltage applied to the x-ray tube occurs. Change in voltage alters intensity distribution and wavelength range; in turn affecting penetrative ability and integrated intensity of the x-ray beam. These fluctuations are not necessarily compensated for by a monitor beam-absorber combination, because while the monitor apparently compensates for intensity changes, there is no compensation for the change produced in effective wavelengths, unless the monitor absorber has identical paths of the same materials contained in the working core.

These remarks are not to be taken as implying that empirically the method may not be made to work by careful standardization of procedure and calibration. But, from the theoretical viewpoint, it would seem that there are a number of pitfalls introduced by employing white x-radiation. On the other hand, the use of monochromatic radiation will unquestionably eliminate or minimize the complications and uncertainties, and lead to improvement in accuracy of measurement. For example, the use of Equation (1) becomes theoretically sound. For another, simplification is achieved because the values of μ/ρ are readily obtainable from standard tables. Finally, a monitor beam becomes an effective compensator for intensity variation with fluctuation in applied voltage.

There are still other advantages to be gained by eliminating the highly penetrative tungsten rays and substituting instead relatively "soft" monochromatic x-rays. Because the absorption coefficients are so much greater in relative value for long

wavelengths, increased sensitivity in detecting small saturation changes should be obtained. It would no longer be necessary to load fluids with highly absorptive materials, foreign to oil well formations, in order to produce detectable intensity changes. The differences in mass absorption coefficients and fluid densities will lead to appreciable differences in transmitted intensities. It will then be possible to make saturation measurements with materials analogous to those found in natural formations. To illustrate this point, approximate values of copper radiation absorption per unit path length of air, oil and water at 20°C have been calculated and are given in the following table.

	$-\ln I/I_o$	Ratio to Air
Air	0.0144	1
Oil[a]	5	350
Water	13	900[b]

[a]Density of 0.8.
[b]The addition of, say, 2 per cent *NaCl* to the water would increase this ratio still more.

It is true that the use of monochromatic radiation "softer" than tungsten will entail a loss in penetrative power and overall x-ray transmission, but this can readily be offset by employing the extremely sensitive Geiger-Muller counter as the detection device. An added advantage given by the Geiger counter is the ability to achieve a predetermined precision measure by prolonging counting time until sufficient x-ray quanta have been tallied.

The ingenious cell calibration method devised by the authors should prove to be a time-saver and of great usefulness to those who choose to employ x-ray absorption techniques in studying fluid saturations.

The proposed procedure for determining three component saturation values appears to be a valuable contribution and promises that this difficult problem will yield to experimental attack. The hope is expressed that experiments to evaluate its practicability will not be delayed.

R. H. Zinszer should like to join me in congratulating the authors for the interesting contribution made by their work. He suggested that, in following up these studies, data collected on a 2 per cent brine solution would be of far greater usefulness than for the 20 per cent solution used in the present work.

REFERENCES

1. Boyer, R. L., Morgan, F., and Muskat, M.: *Trans.* AIME (1947) **170**, 15.
2. Clark, G. L.: *Applied X-Rays*, McGraw-Hill Book Co. (1940) 145.
3. *International Tables for the Determination of Crystal Structure* (1944) **II**, Borntraeger.

AUTHORS' REPLY TO MESSRS. WEST AND GRENALL

In view of the discussions it seems pertinent to reiterate some statements made in the paper and to clarify others.

The purpose of this paper was to outline the method of predicting results and to show experimental confirmation of this method. The theory of x-radiation will allow the calculation of the range and sensitivity of the instruments required to measure an arbitrary effect to a desired degree of accuracy. No matter what combination of fluids, solids and dimensions; x-ray tube voltage, target, current and wavelength band; recording device such as ionization chambers, Geiger counters, electroscopes, fluorescent screens, photographic plates or whatever, any idea based on x-ray absorption may quickly be put to test without recourse to costly experiments.

To allay possible misunderstanding arising from misreading this paper it seems appropriate to reply to the discussions in detail.

Grenall's discussion offers excellent opportunity for clarification of the method of calculation and of some of the theory. The use of white x-ray was dictated by the flexibility required in an exploratory investigation. Consequently an ionization chamber was used because the white beams were too strong to be measured by a Geiger counter and a range of over eight orders of magnitude was used in testing the applicability of the theory. The remarks on Equation (1) are unnecessary since it is stated clearly in the paper that this equation is to be used at one wavelength at a time and that the total effect is to be found by integration. The mass absorption coefficient is constant for each wavelength. However, this points up the confusion that can result from not realizing that the method outlined in Fig. 3 is theoretically correct for all thicknesses of material and for each wavelength emitted by the tube, and there certainly are no pitfalls introduced by white radiation when the method of Fig. 3 is used. For confirmation and details reference should be made to p 512 of Compton and Allison.[3]

The ranges of wavelength and the intensities are given in Fig. 1 for use in computation.

It is true that the voltage and current regulation of the equipment used was not precise. For this reason, as stated in the paper, the monitor tube was used to detect momentary departures of the x-ray output from its average value. Later stabilization of the x-ray output was effective in reducing the aberrations. The polysterene ion chamber insulators were replaced with quartz. Care should be taken in selecting the wavelength of monochromatic x-rays in such a system as outlined in Grenall's table. The values in the table indicate that if 1,000 counts per minute were recorded for an air-filled core, then if the core were oil-filled 6.8 counts per minute would be recorded while, if water-filled, only 0.0023 counts per minute would result. Or, if an oil-filled core gave 1,000 counts per minute a water-filled core would give 0.34 per minute. Consequently, to obtain the advantage of the increase of accuracy with time when using the Geiger counter, one could be obliged to maintain rigid control of his fluid variables for a very long period of time. There are, however, harder monochromatic emanations that would give more reasonable times, but the effects would be similar to those mentioned in the body of this paper.

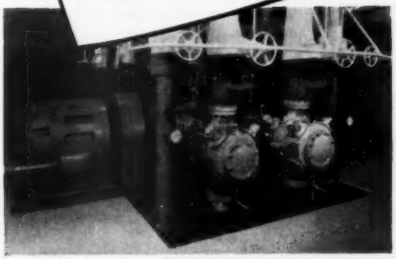
As pointed out by West, no experimental results were included to support Fig. 9. However, data were taken which qualitatively confirmed the theory, but the accuracy was poor due to erratic operation of a circuit and consequently they were not mentioned. The background and zero drift of the ionization chambers were shown to be at least two orders of magnitude smaller than the intensities which were used for the data presented. On the other hand it is usual to have a background count in a Geiger counter at counting rates slow enough to be accurate.

Engstrom's absorption jump method is an interesting application of the Fig. 3 method of predicting results but should be modified in some details. Although the differences in absorption are known the accuracy is poor (p. 527 of Compton and Allison).[3] Moreover, the path length is a linear function of the porosity so non-uniform porosity would have to be handled as described in the body of this paper. Inherent inaccuracies due to the finite size of the wavelength increment $(\lambda_2 - \lambda_1)$, which is not constant (p. 664)[3] should yield to calibration. It is, however, difficult to pick filters and x-ray beams with narrow wavelength bands that coincide with absorption edges. Nevertheless the jump method may have some valuable applications. ★ ★ ★

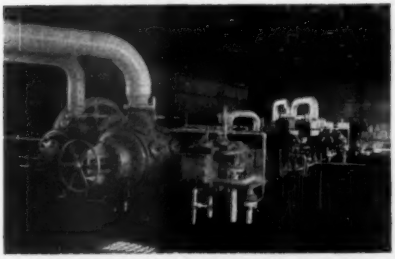
5 types of compressors at Spencer Chemical, signify...

Clark Versatility!

One of nine Clark SCRA, 2750 bhp, steam-engine-driven compressors handling feed gas for ammonia manufacture. Spencer Chemical Co.



Clark CMA-4, 300 bhp, 600 rpm, balanced/opposed, motor-driven compressor for carbon dioxide liquefaction service. Spencer Chemical Co.



Two Clark CRA-6, 1750 bhp, 327 rpm, balanced/opposed, motor-driven compressors for hydrogen and carbon monoxide feed gas service. Spencer Chemical Co.

It may be said that the list of compressors in service at the Jayhawk Works of Spencer Chemical Company reads like a Clark catalog. For there are sixteen Clark compressors, representing five basic models, shouldering the main compressor requirements of this Pittsburg, Kansas plant.

But, the significant aspect of these Spencer installations is not the *number* of Clark units involved, rather the *versatility* of the Clark line that enables complete fulfillment of any and all requirements — no matter how diversified!

In this one plant, for example, are two Clark CRA-6, electric-motor-driven compressors; a Clark CMA-4, electric-motor-driven unit; and nine Clark SCRA, steam-engine-driven models (all illustrated and described herewith); as well as three Clark MA-4 and one Clark RAS-6, gas-engine-driven compressors (not shown).

All of which means simply this: No matter how difficult the problem . . . how specialized the function . . . how diversified the conditions . . . compressor requirements are met completely and most competently by Clark. For, by reason of the versatility of its line, Clark is in the favorable position of being able to recommend without bias and build to anyone's best interests and preferences.

Your nearest Clark representative has data and literature to support these claims.

SEE the difference in . . .

CLARK®

COMPRESSORS

Midget Angle • Right Angle • Big Angle • Electric-Driven • Centrifugal

CLARK BROS. CO., INC. One of The Dresser Industries **OLEAN, N. Y.**

New York • Tulsa • Houston • Chicago • Boston • Washington • Los Angeles • Detroit
Birmingham • Salt Lake City • San Francisco • Buffalo • London • Paris • Ankara, Turkey
Varese, Italy • Buenos Aires • Caracas, Venezuela • Lima, Peru • Bogota, Colombia • New Delhi, India

The Drift of Things

. . . as followed by EDWARD H. ROBIE
Secretary AIME

What We Have and Haven't

No nation has all of the raw materials it needs. Difficulty in securing adequate supplies of those that it lacks has long been a contributory cause, and an important one, of wars. In the world as we would like to have it, every nation would have an equal right to purchase, in the open market, those raw materials it needs. Further, some rules would seem desirable that would prevent a nation with large financial resources from cornering the market for one or more such commodities. In wartime, or when nations are preparing for possible war, there is, of course, a desire to buy up all available supplies of so-called "strategic" materials, not only to assure a domestic supply but to keep supplies out of the hands of present or potential enemies. But, to refer again to the world as we would like to have it, when wars have ended the compelling reason for such monopolistic practices will also have ended. Then the United Nations will really be functioning satisfactorily.

In the meantime we must look out for our needs. The United States is probably in a more satisfactory position with regard to mineral raw materials than any other one country. But the Bureau of Mines indicates that in the current year we are self-sufficient in only nine mineral commodities: sulphur, molybdenum, anthracite, bituminous coal and lignite, phosphate rock, salt, natural gas, helium, and magnesium. In the 90-100 per cent category are nitrates, iron ore, and petroleum. We are 80-90 per cent self-sufficient in ilmenite (titanium) and potash; and 60-80 per cent in copper, zinc, rutile (titanium), and fluorspar. We will produce 55 per cent of our needs for lead, 38 per cent of our bauxite (aluminum) consumption, 26 per cent of antimony, 20 per cent of flake graphite, 10 per cent of cobalt, 9 per cent of mercury, 8 per cent of manganese used for steel, and practically no strategic industrial diamonds, quartz crystals, tin, chromite, nickel, mica, and long-fiber asbestos.

Some of these, notably asbestos and nickel, are available in quantity just across our northern border from a country that experience indicates will always be friendly. For others, supplies are less certain and it would seem wise to maintain stocks sufficiently large for say five years' requirements. An effort is being made to do this, our present achievement in this respect of course not being a matter of record.

Writing Technical Papers

A. J. Murphy is president of the Institute of Metals (the British society) this year, and in his presidential address he refers to the first committee job that he had with that institute — serving on its Publications Committee. He then refers to the work of this committee, and his remarks are so pertinent to the AIME and to our own Technical Publications Committee that some excerpts are worth reprinting here:

"Publications constitute by far the most important activity of the Institute in terms of financial commitment and allocation of staff. . . Therefore, this side of our affairs has to be watched carefully. . . There has been complete unanimity on the necessity of maintaining our high standards of presentation and also on the desirability of publishing all papers submitted which are judged by the Publication Committee to be acceptable on grounds of merit and interest. The Publications Committee, anxious to follow these principles and at the same time mindful of the need for economy, has to be on guard against extravagance in such things as photographs, which are costly to reproduce. . . When referees find the text to be unduly long, it is often rather difficult to suggest exactly where excision or abridgment might be achieved. With the best will in the world, moreover, an author not uncommonly is hard put to it to reduce an already written account by, say, 20 per cent. . . Authors should therefore make a serious effort to effect the greatest condensation consistent with easy reading before submitting their manuscripts. There are few papers which would not actually be improved in clarity by an hour or two of the author's time being devoted to the removal of superfluous words and phrases.

"There are two other causes of unnecessary length in papers. . . One results from an author's failing to realize that a document suitable as a report to a research committee may not be in the best form for a paper intended for presentation to the Institute. . . The second cause of avoidable bulk is the inclination of an author to present his paper as a chronological account of his investigations. . .

"If authors would bear these points in mind and make a special effort to submit a manuscript shorn of all unnecessary trimmings, they would have the satisfaction not only of having produced a more easily assimilable account, but also of knowing that they had made a useful contribution towards keeping down the cost of the Institute's publications."

Saving the Taxpayers' Money

On Page 18 of a mimeographed report of a press conference of the U. S. Atomic Energy Commission we read: "We just wanted to make the report a little shorter this time and save the taxpayers' money."

On Page 2: "*Question:* Morse, when we get through with the report, the other questions are for immediate release? *Mr. Salisbury:* Yes, sir. So let's start now on the report. *Question:* Mr. Salisbury, before you do start, with reference to the time, 12:30 release, tomorrow, is that eastern daylight or eastern standard? *Mr. Salisbury:* Eastern daylight."

Now for even more vital information, let's skip over to Page 19, where they are talking about the dogs on Eniwetok Island used to test the effect of radioactive material on animals: "*Question:* Mr. Dean, back again to the subject of breeders (the reference is to the experimental breeder reactor at Arco, Idaho), what about these dogs that you have on Eniwetok? Are they any special breed? Or just mongrels, or what not? *Chairman Dean:* Not to be confused with the breeder reactor. *Question:* You did refer in your report to breeding your own animals out there, and there has been some question as to what type of dogs, just ordinary dogs, or whether some of your scientists were going out of their way to breed something unusual. *Commissioner Pike:* I don't think you would have that impression if you had seen some of the dogs. *Question:* I did have in mind trying to get one if it is a good dog. Is a dog which has been heavily exposed to radiation known as a 'hot dog'?" ★

Water Analysis by Patterns

Continued from Page 16, Section 1

results of a case where pattern analysis was successfully utilized to determine the formation from which a drill stem test sample originated.

Detection of a Foreign Water and the Determination of Its Source

Oil wells are completed so as to yield a minimum of water, but a break in the cement or a leak in the casing may allow extraneous water to enter. Water yielded by a well in the normal course of operation is usually bottom water, that is, water from the producing formation, while water entering through a leak or cement break may come from some other strata. If sufficient information is available on the composition of the waters in the area, the source of a foreign water may be discovered, and its exclusion brought about with a minimum of trouble and expense.

Fig. 7 presents a case in which water patterns were used to determine the source of water entering a well. Well No. 1 had been producing water of a consistent pattern from formation *A* since its completion, when suddenly the water pattern changed. Another well in the field was producing from formation *B* which was located about 150 ft above *A*. This formation had, of course, been cemented off during completion of Well No. 1. The patterns of various mixtures of *A* and *B* were calculated and plotted as shown. It then became evident that the new pattern resulted from a mixture of approximately 25 per cent water from formation *A* and 75 per cent water from formation *B*. It was therefore concluded that foreign water was entering from formation *B* either through a casing leak or through a break in the cement. Accordingly, the casing was pressure tested and since no leak was found, a cement job was undertaken. At the conclusion of this operation the well was again put on production and at the end of several months the pattern was again similar to that of formation *A*.

CONCLUSIONS

The pattern analysis system presented in this paper offers a simple, practical means of characterizing, comparing, and correlating ground waters. It is particularly useful in facilitating the solution of many petroleum production problems, but can be used to advantage in the study of any question in which water analysis is a factor.

ACKNOWLEDGMENT

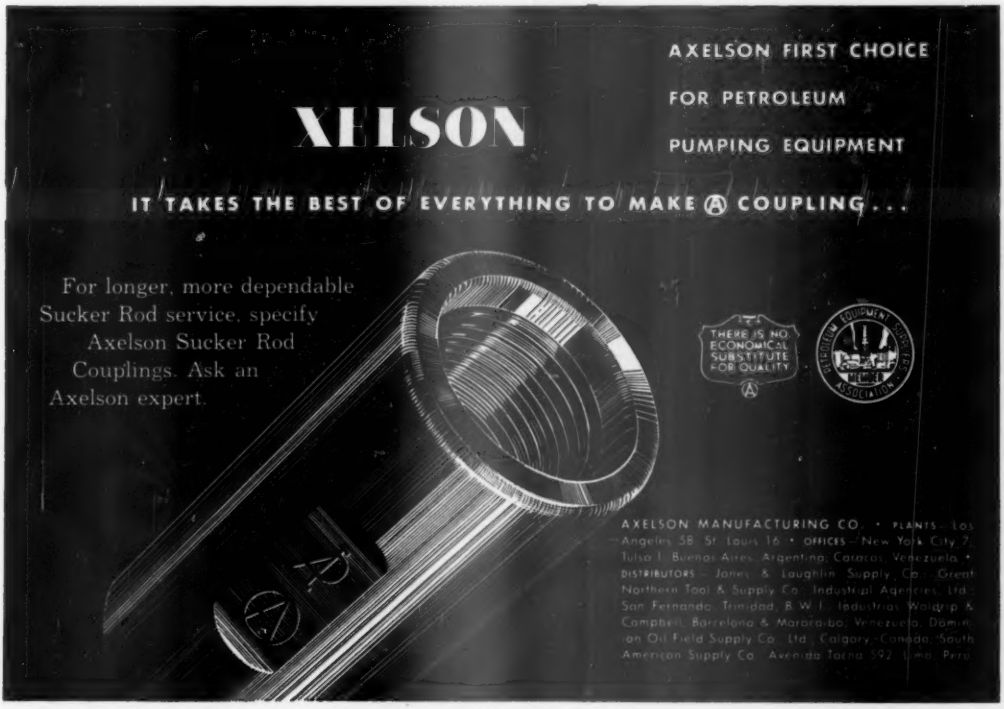
The author wishes to thank The Atlantic Refining Co. for permission to publish this paper, and to acknowledge the advice and encouragement given him by J. H. Sullivan and C. M. Pounders.

Credit for the drawings is extended to Gene Nigh.

REFERENCES

1. Tickell, E. G.: *Report of the California State Oil and Gas Supervisor* (1921) **6**, (9), 5.
2. Reistle, C. E.: *U. S. Bureau of Mines Technical Paper 404* (1927).
3. Parker, J. S., and Southwell, C. A. P.: *Journal of Institution of Petroleum Technologists*, London (1929) **15**, 138-182.
4. Corps, E. V.: *Proc. World Petr. Congress 1* (1933) 338.
5. Lange, A. L.: *Handbook of Chemistry*, Handbook Publishers, Inc., Sandusky, O. (1946) 757.

★ ★ ★


AXELSON FIRST CHOICE
FOR PETROLEUM
PUMPING EQUIPMENT
AXELSON
IT TAKES THE BEST OF EVERYTHING TO MAKE Ⓐ COUPLING...
For longer, more dependable Sucker Rod service, specify Axelson Sucker Rod Couplings. Ask an Axelson expert.
THERE IS NO ECONOMICAL SUBSTITUTE FOR QUALITY
Ⓐ
AXELSON MANUFACTURING CO. • PLANTS – Los Angeles 58, St. Louis 16 • OFFICES – New York City 7, Tulsa 1, Buenos Aires, Argentina, Caracas, Venezuela • DISTRIBUTORS – Jones & Laughlin Supply Co., Great Northern Tool & Supply Co., Industrial Agencies, Ltd., San Fernando, Trinidad, B.W.I., Industrias Wolcrup & Campbell, Barcelona & Maracaibo, Venezuela, Dominion Oil Field Supply Co., Ltd., Calgary, Canada, South American Supply Co., Avenida Tacna 592, Lima, Peru

Personals

GAIL F. MOULTON, second vice-president of the Chase National Bank in the Petroleum Department since 1943, has joined Rockefeller Brothers, Inc., where he will be concerned with oil production activities. After receiving an MS degree from the University of Chicago in 1922, Moulton taught geology for two years, then was engaged in petroleum work for the Illinois Geological Survey. He was later employed by the United Gas Co., the Electric Bond and Share Co., and Ralph E. Davis, Inc., working variously with problems in natural gas, reserve estimates, valuation and appraisal.

+

GEORGE V. COHEE has been appointed chairman of the Department of Geology at the University of Arkansas, Fayetteville. He will also maintain part-time work with the U. S. Geological Survey.

+

R. W. RUSSELL is now a member of the technical staff of the San Juan Oil Company, Dallas, Tex. He is a graduate geologist and petroleum engineer from Texas A&M College, and was formerly an exploitation engineer for the Shell Oil Co. in West Texas.

+

WILLIAM E. STILES has joined Buffalo Oil Co. as vice-president in charge of engineering. Stiles, formerly manager of sales and assistant to the president of Core Laboratories, Inc., will direct the engineering development of the company's producing properties from Buffalo's headquarters in Dallas, Tex. The Buffalo Oil Co. employed secondary recovery techniques for several years, and at the present time has interests in a number of gas injection and water flood projects. Stiles will direct the engineering aspects of Buffalo's expanded program for acquiring additional secondary recovery properties and new reserves.

RICHARD M. SPARKMAN is now assistant production manager for Jack B. Robert, independent operator with headquarters in Breckenridge, Texas. Formerly with the Lane-Wells Co., Sparkman had advanced from field engineer in the Gulf Coast Division to field service engineer in the Los Angeles office. He had held the latter position for two and one-half years.

+

ED SAYE, III, district sales engineer for the Lane-Wells Co., has been appointed director of the company's new sales office in Denver, Colo. He has been active in the mid-continent area since 1946 when he joined Lane-Wells. Saye has spent considerable time in both the operating and engineering departments as well as the sales activities of the company. While serving in the Marine Corps during the last war, he took graduate training in radar and electronics at Harvard and M.I.T.

+

MARTIN JAMES GARRITY has accepted a position in the engineering department of Union Oil Co., Los Angeles refinery, at Wilmington, Calif.

+

HERBERT JOSEPH HARRIS is now with The Texas Co., Anaheim, Calif.

+

W. C. HAYES has left the State University of Iowa and is now assistant professor of mineralogy and petrology at Texas Technological College, Lubbock, Tex.

+

ROBERT L. HALVORSEN is now employed by the Stanolind Oil and Gas Co., Andrews, Tex., as an engineer trainee.

+

EWEL EDWIN VAUGHAN has accepted a position with the British-American Oil Producing Co., Grayville, Ill.

+

ELLIS L. ANDERS, JR., is now chief reservoir engineer for the International Petroleum Co., Ltd., in Talara, Peru. For the past three years he has been associate professor of petroleum engineering at the University of Kansas.

RAY A. HANCOCK, previously assistant Pacific Coast division manager of Lane-Wells Co., has been transferred to Oklahoma as assistant mid-continent division manager. In his 13 years with the company, Hancock has held varying managerial positions, including Pacific Coast division operating superintendent, sales manager, and finally assistant manager of that division. During 1950, he was sub-district superintendent at Odessa, Texas. Hancock is a graduate of the University of California with a BS in petroleum engineering.

+

MARVIN C. ZEID has joined the Atlantic Refining Co., Greggton, Tex., as a petroleum engineer.

+

CHESTER L. DOYLE has been advanced to assistant chief petroleum engineer in the exploration department, General Petroleum Corp., Vernon, Calif.

+

JOSEPH R. GROSS, Shell Oil Co., has been transferred from Franklin, La., to St. James, Minn.

+

JOHN ANTHONY GRISWOLD is now with the National Supply Co., Casper, Wyo.

+

DONALD L. KATZ, professor of chemical engineering, has been appointed to the chairmanship of the Department of Chemical and Metallurgical Engineering at the University of Michigan. He will succeed George Granger Brown, now Dean of the College of Engineering. Katz has been a member of the Michigan faculty since 1936. He was previously employed by the Phillips Petroleum Co. in Bartlesville, Okla., where he conducted research on vapor-liquid equilibria at high pressures and on reservoir engineering. Katz has been author or co-author of more than 100 technical publications, and has also served as consulting engineer to companies, associations and government agencies.

Sub-Surface Correlations

Continued from Page 14, Section 1

are rare in ancient sediments, that illite is the dominant clay in most massive shales, that changes are greater in marine and brackish waters. He also pointed out that the synthesis of clays is being studied which is indicating that the presence of certain chemical elements play a great role in the formation of clay minerals.

Killian then illustrated graphically the results of some D.T.A. that had been done in the East Venezuela Field where considerable work had been done with this process. Ditch samples were used exclusively for obtaining the unknown sample and tops of microfaunal horizons were picked on the results of this work which, after later information was obtained, checked excellently with the zonal tops picked by the micropaleontologists.

Kilian feels that D.T.A. is a workable, practicable and fit tool; that it is easy to use as a correlative tool to anyone acquainted with logging; that it is fast and relatively inexpensive; that it permits better mud engineering since it gives a good mineralogical picture of the chemical composition of the formation being drilled through at the time. ★ ★ ★

Illinois Basin Reefs

Continued from Page 13, Section 1

tional structures. Production from the reef core itself presents some unusual features. There appears to be no consistent oil-water contact within the reef body, at least in the case of Marine, the best known example. Some oil is produced at least 140 ft beneath the position at which water is produced in neighboring wells. However, the reservoirs are all hydrostatically connected, as the static fluid levels are very consistent and have apparently declined in untapped reservoirs to keep pace with the pressure drop in the field as a whole. ★ ★ ★

E. G. Bailey to Receive 1952 John Fritz Medal

E. G. Bailey, vice-president of the Babcock & Wilcox Co., has been selected to receive the John Fritz Medal for 1952 "for outstanding achievements in the field of combusion and distinguishable service to his fellows in advancing the engineering profession." The award is jointly sponsored by the four Founder Engineering Societies and is often referred to as the highest award in engineering, being given for scientific or industrial achievement in any field of pure or applied science. Bailey is a past president of the American Society of Mechanical Engineers and has been a prominent member of the AIME, Coal Division, for the last 19 years. ★ ★ ★

Price of '51 Transactions To Remain Same

Transactions volumes for the year 1951, to be issued early in 1952, will be sold at the same prices as for 1949 and 1950. To AIME members who regularly receive them, or who order them when they pay their 1952 dues, the price will be $3.50 for the bound book. Otherwise the price to members is the non-member price of $7 less 30 per cent, or $4.90. The usual three volume will be published: No. 190, Mining Branch; No. 191, Metals Branch; and No. 192, Petroleum Branch. Each will consist of the Transactions material published in the respective journal during 1951, a title page and index.

Microfilm reproductions of AIME journals, including the Transactions section, are available from University Microfilms, Ann Arbor, Mich. ★ ★ ★

Mailing of 1952 Dues To Begin in Fall

Mailing of 1952 dues bills to AIME members will begin in the early fall and be completed by the end of the year. An early remittance will be appreciated, both to lessen the year-end peak in the accounting department and to save the expense of follow-ups. Officially, dues are payable Jan. 1. Mailing of publications to those in arrears is suspended with the March issues of the journals. Resignations must be received by March 31, otherwise a member becomes indebted for his 1952 dues. Members are carried on the rolls for two years without payment of dues before their membership is finally terminated. These arrears must be paid up in order that a member be again considered "in good standing." However, Student Associates, and also Junior Members who have attained the age of 33 during 1951 and are thus forced to change status, will be dropped at the end of March unless remittance for 1952 dues at the rate appropriate for the higher grade of membership has been received. This permits later reinstatement without any charges for arrears.

Address Change Procedure

If either your address or position changes you owe it to yourself and friends to let AIME headquarters know a month before the change is made or as soon as possible if you can give your future address accurately. Please following these suggestions:

1. Give your name and the address to which publications and correspondence should be sent. Mark this: "Publications address."

2. Give your name, title, or company position, and your address the way you want it to appear in the next Directory. Mark this: "Directory listing."

3. A short personal item for publication in the monthly journal will be appreciated.

Send your advice, by postal card or letter, to: AIME, 29 W. 39th St., New York 18, N. Y.

Junior Members to Get New Mudd Fund Book

A new book is to be made available later in the year to new Junior Members, as a gift of the Seeley W. Mudd Memorial Fund. It is *The Formation of Mineral Deposits*, by Alan M. Bateman, which is being published by John Wiley & Sons. The Fund Committee has purchased 1,000 copies, and the volume will be included in the list for Junior Members as soon as published. The price of the book to the public will be $5.50. ★ ★ ★

AIME Board Meeting To Be held Dec. 5

The December meeting of the Board of Directors, AIME, in New York, will be held on Dec. 5 instead of Dec. 12, as previously announced. An extra meeting of the Board has also been scheduled for Los Angeles in the week of the meetings of the American Mining Congress and of the Southern California Section. The date will probably be Oct. 25. ★ ★ ★

– It's a Fact –

Since 1926, general living costs have risen 44 per cent, food has increased 61 per cent and house furnishings are up 76 per cent. In the same period, the price of gasoline, without taxes, has dropped from an average of 20.9 cents per gallon to 20.5 cents per gallon, a decrease of two per cent. But taxes on gasoline are 177 per cent higher than they were in 1926.

Employment Notices

The JOURNAL will post notices of men and jobs available. Companies and AIME members are invited to use this space, for which there is no charge. Except as noted below, address replies to: Code (appropriate number), JOURNAL OF PETROLEUM TECHNOLOGY, 408 Trinity Universal Bldg., Dallas 1. Show return address on envelope. These replies will be forwarded unopened and no fees are involved.

Replies to the positions coded Y5908, Y5944, Y6021 and M-624 below should be addressed to: Engineering Societies Personnel Service, 8 West 40th St., New York 18, N. Y. The ESPS, on whose behalf these notices are published here, collects a fee from applicants actually placed.

POSITIONS

♦ Engineers. (a) Oil refinery process design engineer, 30-40, chemical or mechanical engineering graduate, with actual oil refinery distillation process design work on cracking plants or equivalent. Will supervise engineers and draftsmen in the design of all types of distillation units from flow plans and data. Must be able to discuss with oil refinery experts all phases of oil refinery design. Salary open. (b) Oil refinery field maintenance and construction superintendent, 30-60, with actual experience in the field working for an oil company or for a contractor who has contract work in an oil refinery performing the following work: hiring and supervising all classes of mechanics and assigning them to oil refinery maintenance or construction as required. Salary open. Location, New York metropolitan area or Gulf Coast area, or both. Y5908.

♦ Accounting engineer with at least three years' experience on preparation of operating cost data for staff position with consultant at oil refinery project. Knowledge of Spanish desirable. Salary, $7,200 a year plus living expenses. Location, Venezuela. Y5944.

♦ Sales engineer with oil field experience, to sell barite weighing material to drilling contractors and oil companies in Louisiana and Texas. Salary open. Y6021.

♦ Petroleum engineer or technologist for secondary recovery research laboratory in eastern United States. Advanced degree or production research experience preferred. Liberal publication policy. Opportunity to gain first hand experience in secondary recovery through coordinated laboratory and field research. Salary open. Reply giving educational background and experience. Code 535.

♦ Two research engineers, with MS degrees and two to five years' field experience are desired as permanent additions to an expanding staff. The work includes research in fundamentals of reservoir performance and secondary recovery, and involves application of newly developed reservoir engineering techniques in studies of foreign and domestic pools. Location, Tulsa. Address replies, giving full information, to: Chief of Research, The Carter Oil Co., P.O. Box 801, Tulsa, Okla.

PERSONNEL

♦ Mineral economist, 28, married, BS mineral economics and geology, Penn State College; MA resources and economics, University of Texas. Experienced coal mining, concentrating plants and manufacturing of copper products. Desires responsible position mining or iron and steel industry in sales engineering or other specialized work relating to this field. M-624.

♦ Graduate petroleum engineer with 15 years' experience desires operating or engineering position with progressive independent company. Experience includes supervision of drilling, testing, completing, producing, working over, purchasing equipment, installing equipment, and supervising personnel. Also experienced in office records, reports, maps, and have made various economic surveys. Presently employed with headquarters in North Central Texas. Code 157. ★ ★ ★

Proposed for Membership, Petroleum Branch

Total AIME membership on Sept. 30, 1951, was 17,234; in addition, 2,521 Student Associates were enrolled.

ADMISSIONS COMMITTEE

Thomas G. Moore, Chairman; Carroll A. Garner, Vice-Chairman; George B. Carless, F. W. Hanson, Albert J. Phillips, Lloyd C. Gibson, R. D. Mollison, John T. Sherman. Alternates, A. C. Brinker, H. W. Hitzrot, Plato Malozemoff, Ivan Given, T. D. Jones, W. A. Clark, Jr.

Institute members are urged to review this list as soon as the issue is received and immediately to wire the Secretary's office, night message collect, if objection is offered to the admission of any applicant. Details of the objection should follow by air mail. The Institute desires to extend privileges but does not desire to admit persons unless they are qualified. Objections on applications should be received on the 15th of the month following publication in PETROLEUM TECHNOLOGY.

In the following list C/S means change of status; R, reinstatement; M, member; J, Junior Member; A, Associate Member; S, Student Associate; F, Junior Foreign Affiliate.

CALIFORNIA

Altaras — Ackley, Ronald L. (J) (C/S-S-J).
Compton — Briggs, Robert D. (J) (R,C/S-S-J).
Montebello — Sandiford, Burton B. (A).
San Francisco — Blunden, Richard L. (M) (R,C/S-J-M); Judah, Russell J. (J) (R, C/S-S-J).
Taft — Newberg, Peter L. (J) (C/S-S-J).

COLORADO

Golden — Villarreal, Juan F. (J) (C/S-S-J).

KANSAS

Wichita — Brown, Charles S. (M) (C/S-A-M); Hanson, Maurice E (M).

LOUISIANA

Franklin — Chalmers, Irwin R. (J) (R,C/S-S-J).

MASSACHUSETTS

Wollaston — Barry, William V. (J) (C/S-S-J).

MINNESOTA

Minneapolis — Boyd, Walter E. (A).

NEW HAMPSHIRE

Tamworth — Blackey, Edwin A., Jr. (J) (R,C/S-S-J).

NEW MEXICO

Farmington — Gibson, Alfred R. (J) (C/S-S-J).
Jal — Sweitzer, Paul D., Jr. (J) (R,C/S-S-J).

NEW YORK

New York — Hazen, George H. (M).

OKLAHOMA

Edmond — Spencer, Lester B. (M) (R,C/S-J-M).
Tulsa — Kilgren, Evert W. (M); Paul, James R. (J) (R,C/S-S-J); Stolz, Gustav, Jr. (J) (C/S-S-J); Wilkins, Robert B. (M) (C/S-A-M).

PENNSYLVANIA

Altoona — McWilliams, Ronald E. (J) (C/S-S-J).

TEXAS

Amarillo — Garner, Reynold M., Jr. (J) (R, C/S-S-J).
Bay City — Waggoner, Bert L. (J).
Beaumont — Guinn, David C. (J) (C/S-S-J).
Bellaire — Rankin, Horace A. (M).
Brownfield — Bass, Daniel M., Jr. (J) (R, C/S-S-J); Linton, William J. (J).
Corpus Christi — Denman, Richard H (A) (R,C/S-S-A); Snelson, Lawrence W., Jr. (J) (R,C/S-S-J).
Dallas — Baron, Arnold E. (J) (R,C/S-S-J); Turner, William J. (J) (C/S-S-J).
El Paso — Rowling, Reese M. (J).
Fort Worth — Hill, James R. (J) (R,C/S-S-J); O'Quinn, Percy C. (J) (R,C/S-S-J).
Freer — Southerland, Willis H. (M).
Houston — Lloyd, Samuel H., III (J); Nicodemus, William F. (J) (R,C/S-S-J); Payne, Lyle (M).
Midland — Randerson, Luther W. (M) (C/S-A-M).
Port Lavaca — Reiss, Royal W. (M).
Selman City — Simpson, William R. (A) (R,C/S-S-A).

CANADA

Alberta — Barthelemy, Joseph E., Jr. (J) (R,C/S-S-J).

MEXICO

N. Laredo, Tamps. — Guitierrez-Garcia, Santiago (M) (C/S-A-M). ★ ★ ★

Professional Services

This space available only to: AIME members. Rates upon request.

AMSTUTZ AND YATES, INC.
Petroleum Engineers and Geologists
Estimates of Oil & Gas Reserves
Property Valuations, Reservoir Analyses
Geologic Investigations
406 KFH BLDG., WICHITA 2, KANS.

BERGER AND PISHNY
Consulting Geologists and Engineers
901 Commercial Standard Bldg.
Fort Worth 2, Texas
Walter R. Berger — Chas. H. Pishny

JOHN G. CAMPBELL, CHEMIST
Licensed for
Fluorometric Analysis of Well Cuttings
Podbielniak & Charcoal Analyses
Waters - Oil Field Brines - Cores
CORPUS CHRISTI, TEXAS — PHONE 4-5612

CHEMICAL & GEOLOGICAL LABORATORIES
Consultants - Investigations - Evaluations
James G. Crawford.....Chemical Engineer
H. E. Summerford.....Petroleum Geologist
F. Raymond Wheeler....Petroleum Engineer
P. O. BOX 279 — CASPER, WYOMING

CRUTCHFIELD AND PRUETT
CONSULTING PETROLEUM ENGINEERS
224 Wilson Building
CORPUS CHRISTI, TEXAS
John W. Crutchfield — *Horton T. Pruett*

DENTON-SPENCER COMPANY, LTD.
CONSULTING PETROLEUM ENGINEERS
Lancaster Bldg. — Calgary, Alberta

EARLOUGHER ENGINEERING
Petroleum Consultants - Core Analyses
Specializing in Secondary Recovery
Investigations - Appraisals - Operations
311-319 East Fourth Street
TULSA 3, OKLAHOMA
Office 2-5129 — Laboratory 2-6139

FITTING & JONES
Engineering and Geological Consultants
Petroleum — Natural Gas
Box 1637
223 S. Big Spring St. — Midland, Texas

MICHEL T. HALBOUTY
CONSULTING GEOLOGIST
AND PETROLEUM ENGINEER
Shell Building
Houston 2, Texas — Phone PR-6376

RICHARD V. HUGHES
Secondary Recovery of Oil
Mining Building — Stanford University
Stanford, California

PETROLEUM CONSULTANTS
Engineering and Geology
E. O. Bennett — James O. Lewis
D. G. Hawthorn — William Hurst
M. D. Hodges
1552 Esperson Bldg. — Houston, Texas

KELLER & PETERSON
Petroleum Consultants
Reserve Estimates — Property Appraisals
Petroleum and Geological Engineering
Reservoir Analysis
MIDLAND, TEXAS
P. O. Box 1787 — Phone 4-6181
W. O. Keller — L. F. Peterson

JAMES A. LEWIS ENGINEERING, INC.
Petroleum Reservoir Analysts
Core Analysis, Relative Permeability,
Restored State, Resistivity, Flood Tests
Comprehensive Reservoir Studies
Pressure Maintenance, Secondary Recovery
6923 Snider Plaza — P. O. Box 237
Dallas 5, Texas — Evansville 8, Ind.

W. T. MENDELL
Engineering & Geological Consultant
Second National Bank Building — Houston, Texas — CApital 7612

CLEVELAND O. MOSS
CONSULTING PETROLEUM ENGINEER
Estimates of Oil and Gas Reserves
Valuation—Production Problems—Proration
208 MIDCO BLDG. — TULSA 3, OKLA.

OILFIELD SERVICE COMPANY
Electric Logs — Gamma Ray — Caliper
Water Input Profiles
Specializing in Secondary Recovery
CHANUTE, KANSAS

ERNEST K. PARKS
CONSULTING PETROLEUM ENGINEER
Planning, Direction and Examination of
Oilfield Operations, Estimates of Oil and
Gas Reserves, Oil Property Valuation
614 S. HOPE STREET, LOS ANGELES 17, CALIF.
Telephone: VanDyke 4659

WALTER ROSE
Box 1581 — *University Station*
AUSTIN, TEXAS

E. E. REHN
Consulting Petroleum Geologist
Oil Exploration
Woods Building, 624 Locust Street
EVANSVILLE, INDIANA

SOL SMITH
CONSULTING ENGINEER
PETROLEUM AND NATURAL GAS
Reserves — Deliverability
Oil and Gas Proration
826 BROWN BUILDING
AUSTIN, TEXAS — PHONE: 89498

WM. H. SPICE, JR.
Consulting Geologist
2101-03 Alamo National Building
SAN ANTONIO 5, TEXAS

R. W. TESCH
PETROLEUM CONSULTANT
Valuation — Development — Management
Electric Bldg. — Fort Worth, Tex.

TRAFFORD & ASSOCIATES
Geological, Petroleum Engineering and Management Consultants
E. Trafford, R. Pat, P. Klaui
Wales Hotel Bldg., 10th Floor, Calgary, Alberta
Phones 61212, 61224, 63132

JOSEPH B. UMPLEBY
6214 PARK LANE
DALLAS 5, TEXAS

HAROLD VANCE
CONSULTING PETROLEUM ENGINEER
Pet. Engr. Dept. — A & M College
College Station, Texas

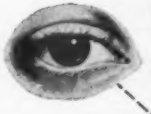
Iran and World Oil

Continued from Page 12, Section 1

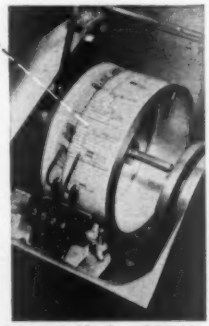
At first glance, one might think that a large increase in tanker tonnage would be required to carry these products from various scattered supply points to the markets formerly supplied out of Abadan. It is true that supplying the remote Indian and Far East consumption from alternate sources is wasteful of transportation. However, there are compensating savings. A substantial part of Abadan's production went to Europe, and, to the extent this area can be served from the United States and Caribbean, the advantages of central location make possible some transportation savings. In addition, Middle East crude which has recently been imported into the United States is being diverted to Europe, and replaced with Western Hemisphere crude. Substantial tonnage savings are involved here. Overall it appears probable that the Iranian supplies can be largely replaced without substantial net increases in tonnage requirements.

It is obvious, of course, that a world-wide rearrangement of the flow of crude and products is not a simple matter. Many problems are involved in arranging these drastic changes in supply routes. Temporary shortages might develop prior to full solution of these many supply problems. Aviation gasoline and residual fuel oil present especially difficult supply problems. It seems clear, however, that any such shortages will be small when viewed as a percentage of world consumption. The vitality and flexibility of the world oil industry which has been developed in dealing with a vigorous growing demand now stands it in good stead in meeting a world supply emergency. ★ ★ ★

SEE formation changes *as you drill* WITH GEOLOGRAPH



With Geolograph, you actually watch the drilling change as the bit bites into contrasting strata — foot by foot! You'll find that this subsurface control, while drilling, results in a higher percentage of successful drill stem tests; fewer and more correctly placed cores; accurate determination of net pay thickness and elimination of many depth corrections!



Abilene, Houston, Odessa, Lubbock and Wichita Falls, Texas - Bakersfield, Calif. - Shreveport and Baton Rouge, La. - Casper, Wyo. - Oklahoma City, Okla.

"TIME WILL TELL"

THE GEOLOGRAPH CO. INC.

P. O. Box 1291 Oklahoma City 1, Okla.

Advertisers' Index

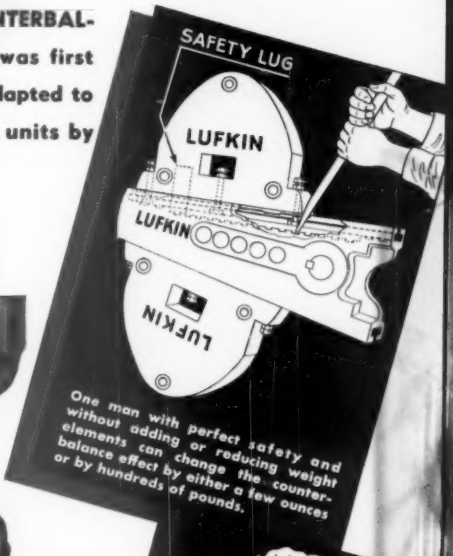
	Page
A-1 Bit & Tool Co. — *Calvin L. Clausel, Jr., Houston*	Sec. 1—4
American Iron & Machine Works — *Lowe Runkle Co., Oklahoma City, Okla.*	*
Axelson Manufacturing Co. — *Heintz & Co., Los Angeles, Calif.*	Sec. 2—3
Baker Oil Tools, Inc. — *Theo. M. Martin Co., San Gabriel, Calif.*	*
B and W Incorporated	Sec. 1—5
Clark Bros. Co., Inc. — *Harold Warner Co., Buffalo, N. Y.*	Sec. 2—1
Core Laboratories, Inc. — *Duvall Williams, Dallas, Tex.*	*
Dowell Incorporated — *MacManus, John & Adams, Inc., Detroit, Mich.*	Sec. 1—8
Eastman Oil Well Survey Co. — *Ted Workman Advertising, Dallas, Tex.*	*
Geolograph Co., Inc. — *Lowe Runkle Co., Oklahoma City, Okla.*	Sec. 2—8
Geophysical Research Corp. — *Gibbons Advertising Agency, Tulsa, Okla.*	*
Halliburton Oil Well Cementing Co. — *Hill & Christopher, Los Angeles, Calif. Bachrodt, Newell, O'Kane and Gano, Chicago, Ill.*	Sec. 1—1, 7
Hughes Tool Co. — *Foote, Cone & Belding, Houston*	*
Johnston Oil Field Service, M. O. — *Dozier-Eastman & Co., Los Angeles, Calif.*	Sec. 1—2
Keystone Development Corp. — *Brennan Advertising Agency, Houston, Tex.*	*
Lane-Wells Co. — *Darwin H. Clark Co., Los Angeles, Calif.*	Sec. 1—20
Lufkin Foundry & Machine Co. — *Cudlipp Advertising Agency, Lufkin, Tex.*	Third Cover
Magnet Cove Barium Corp. — *Rives, Dyke and Co., Houston, Texas*	*
McCullough Tool Co. — *R. P. Casterline Advertising, Los Angeles, Calif.*	*
Lee C. Moore Corp. — *Watts, Payne Advertising, Tulsa, Okla.*	*
Oil Base, Inc. — *Dozier-Eastman & Co., Los Angeles, Calif.*	*
Otis Pressure Control, Inc. — *Don Goodrich, Dallas, Tex.*	*
Professional Services	Sec. 2—7
The Second National Bank, Houston, Tex. — *Gano, Bachrodt, Edwards, Inc., Houston, Tex.*	*
Sperry-Sun Well Surveying Co. — *Wallace Davis & Co., Houston*	*
Sinclair Research Laboratories, Inc. — *Kenyon & Eckhardt, Inc., Adv., New York*	*
United Geophysical Co., Inc. — *Dozier-Eastman & Co., Los Angeles, Calif.*	Fourth Cover
Welex Jet Services, Inc. — *Evans & Assoc. Advertising, Ft. Worth, Tex.*	*
Well Surveys, Inc. — *Watts, Payne Advertising, Tulsa, Okla.*	*
Zublin Flexible Drill Pipe — *Roy F. Irvin Advertising, Los Angeles, Calif.*	Sec. 1—6

* In previous issues

LUFKIN LEADS!

The TROUT COUNTERBALANCED CRANK was first introduced and adapted to all field pumping units by LUFKIN in 1923.

This crank, along with many other patented improvements, have contributed to LUFKIN'S imminent leadership in the industry.



One man with perfect safety and without adding or reducing weight elements can change the counterbalance effect by either a few ounces or by hundreds of pounds.

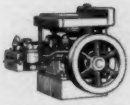
On the smaller Lufkin Units, no tools, other than the wrench furnished with the unit, are necessary to enable one man to change counterbalance as desired.

LUFKIN FOUNDRY & MACHINE COMPANY
LUFKIN, TEXAS

Branch sales and service Houston, Dallas, New York, Tulsa, Los Angeles, Seminole, Oklahoma City, Corpus Christi, Odessa, Kilgore, Wichita Falls, Casper, Wyoming, Great Bend, Kansas.

Lufkin Equipment in CANADA is handled by
THE LUFKIN MACHINE CO., LTD. 14321 104th Avenue, Edmonton, Alberta, Canada

LUFKIN PUMPING UNITS

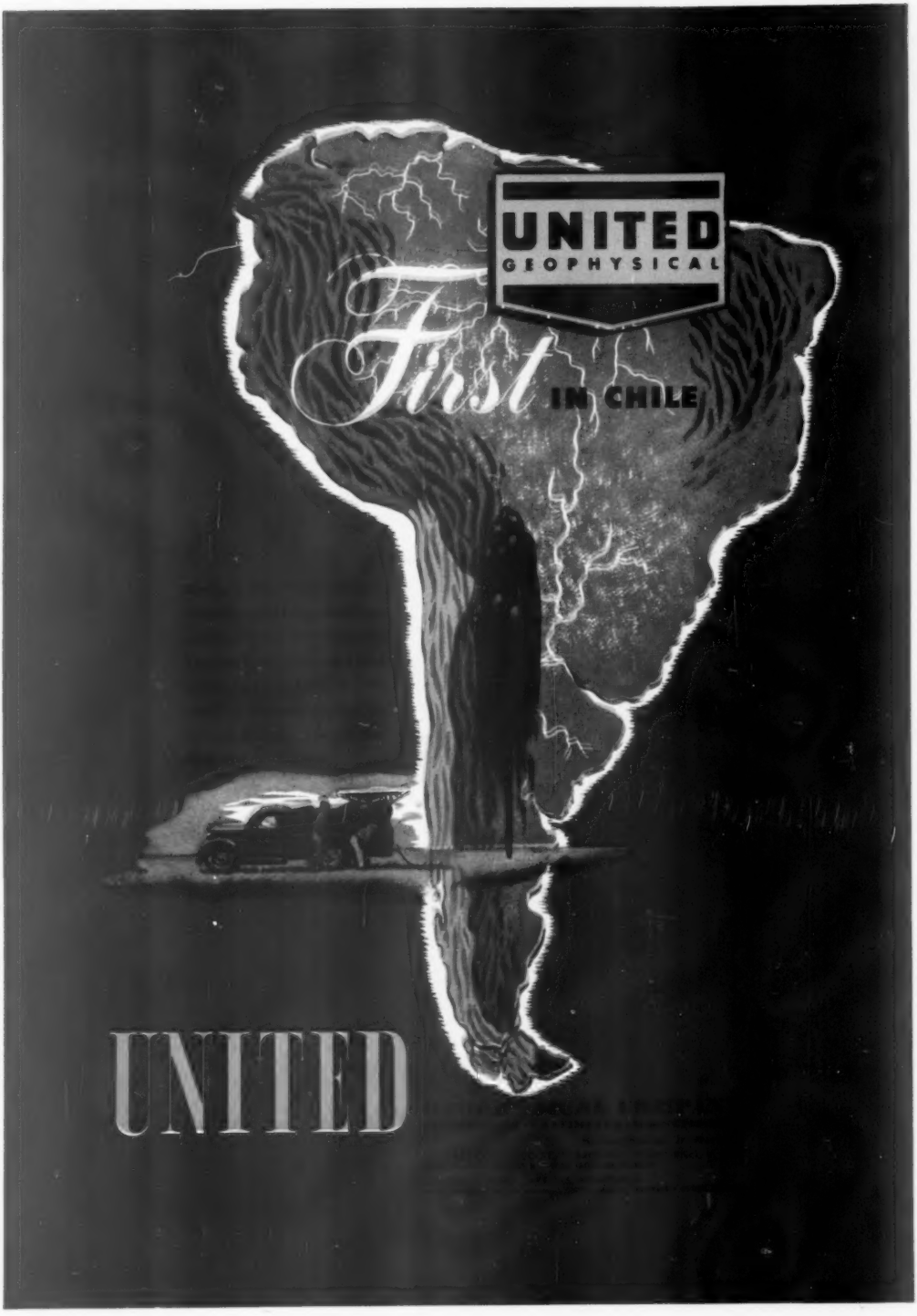


LUFKIN-COOPER-BESSEMER ENGINES

LUFKIN OIL FIELD AND INDUSTRIAL TRUCK TRAILERS

INDUSTRIAL SPEED REDUCERS AND INCREASERS

DIVISION LUFKIN FOUNDRY & MACHINE COMPANY
INDUSTRIAL, MILL AND AUTOMOTIVE SUPPLIES


UNITED
GEOPHYSICAL
First IN CHILE
UNITED